National Aeronautics and Space Administration

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Earth Science Reference Handbook

A Guide to NASA's Earth Science Program and Earth Observing Satellite Missions

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Abstract

The Earth Science Reference Handbook provides a guide to the satellite missions and other elements of NASA's Earth science program. This volume updates the 1999 EOS Reference Handbook, now that the major missions of the Earth Observing System (EOS) have been launched and are transmitting data, and broadens the coverage to include not just EOS but also additional NASA Earth science missions. The book begins with overviews of NASA's Earth science program and its following aspects: Earth observations, the data and information system and policies regarding the data, the applied sciences program, the education program, the technology program, and the collaborative efforts with other nations and with other agencies within the U.S. This preliminary material constitutes the first 25% of the book. The remaining 75% centers on NASA's satellite Earth-observing missions (many of them joint with other nations and/or agencies), beginning with the Active Cavity Radiometer Irradiance Monitor Satellite (ACRIMSAT) and proceeding alphabetically through the Upper Atmosphere Research Satellite (UARS). The chapters on individual missions include summaries of the mission and its science goals, descriptions of each instrument on the spacecraft and its relevance to the mission, a list of data products, points of contact, and a list of references. The program as a whole is collecting hundreds of Gigabytes a day of data about the Earth system; these data are being processed by numerous data centers and are being made available to the research community, weather forecasters, and a wide variety of additional users.

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Acknowledgements

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In addition to these individuals, the table below lists major contributors, including reviewers, to each section of the handbook. The names in *italics* served as *primary EOSPSO points of contact* for developing content. For the Missions section Robert Wolfe of NASA GSFC also helped significantly by providing data set start and, when appropriate, end dates for past and ongoing missions.

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Acronyms and Abbreviations

AERO	Aerospace Corporation
CU	University of Colorado
Col U	Columbia University
CSU	Colorado State University
EORC	Earth Observation Research Center
EOS	Earth Observing System
EOSPSO	EOS Project Science Office
ESR	Earth & Space Research
FMI	Finnish Meteorological Institute
GISS	NASA Goddard Institute for Space Studies
GSFC	NASA Goddard Space Flight Center
HQ	NASA Headquarters
HU	Hampton University
JAXA	Japan Aerospace Exploration Agency
KNMI	Royal Dutch Meteorological Institute
LASP-CU	Laboratory for Atmospheric and Space Physics—University of Colorado
LaRC	NASA Langley Research Center
LMTO	Lockheed Martin Technical Operations
JPL	NASA Jet Propulsion Laboratory
MIT	Massachusetts Institute of Technology
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
OSU	Oregon State University
OU	Oxford University
RSS	Remote Sensing Systems
SSAI	Science Systems and Applications Incorporated
SSC	NASA Stennis Space Center
UAH	University of Alabama, Huntsville
UMBC	University of Maryland, Baltimore County
USGS	United States Geological Survey
UT	University of Toronto
UTCSR	University of Texas Center for Space Research

NASA’s Earth Science Program

Introduction

NASA’s Earth science program is dedicated to understanding the total Earth system and the effects of natural and human-induced changes on the global environment. The vantage point of space provides information about Earth’s land, atmosphere, ice, oceans, and biota that is obtainable in no other way. NASA is studying the interactions among these components to advance the new discipline of Earth system science, with a near-term emphasis on global climatic change. Our research results contribute to the development of sound environmental policy and economic investment decisions.

NASA develops innovative technologies and applications of remote sensing for solving practical societal problems in food and fiber production, natural-hazard mitigation, regional planning, water resources, and national-resource management in partnership with other Federal agencies, with industry, and with state and local governments. Earth science discoveries are shared with the public to enhance science, mathematics, and technology education and increase the scientific and technological literacy of all Americans. Earth science combines the excitement of scientific discovery with the reward of practical contributions to the sustainability of our home planet.

Background

In the 21st century, planet Earth faces the potential hazard of rapid environmental changes, including climate warming, rising sea level, deforestation, desertification, atmospheric ozone depletion, increased acid rain, and reduced biodiversity. Such changes could have a profound impact on all nations and on the natural system, but many important scientific questions remain unanswered. For example, while most climate scientists agree that global warming is occurring, details on its magnitude, timing, and causes (especially at the regional level) are quite uncertain. Additional information on the rate, causes, and effects of global change is essential to developing the understanding needed to cope effectively with it. NASA is working with the national and international scientific communities to establish a sound scientific basis for addressing these issues through research efforts coordinated under the U.S. Climate Change Science Program (CCSP), encompassing the Climate Change Research Initiative (CCRI) and the U.S. Global Change Research Program (USGCRP); the International Geosphere-Biosphere Program (IGBP); and the World Climate Research Program (WCRP). The strategy of NASA’s Earth Science Program is explained in the document, *Earth Science Enterprise Strategy* (NASA 2003), which can be accessed at: science.hq.nasa.gov/strategy/index.html.

Scientific research shows that Earth has continually undergone changes throughout its history and continues to change. Human activity has altered the condition of Earth by reconfiguring the landscape, by changing the composition of the atmosphere, and by stressing the biosphere in countless ways. There are strong indications that natural change is being accelerated by human intervention. In its quest for improved quality of life, humanity has become a force for change on the planet, building upon, reshaping, and modifying nature—often in unintended ways.

The by-products of human activities, such as carbon dioxide, methane, nitrous oxide, and other gases, once in place in the atmosphere, trap heat emitted from Earth’s surface, thus potentially warming the global atmosphere. Measurements over the past several decades have documented a rapid rise in concentrations of these greenhouse gases (Figure 1). Changes in other variables, such as global cloudiness, concentration of atmospheric dust particles, sea ice concentrations, and ocean-circulation patterns, also

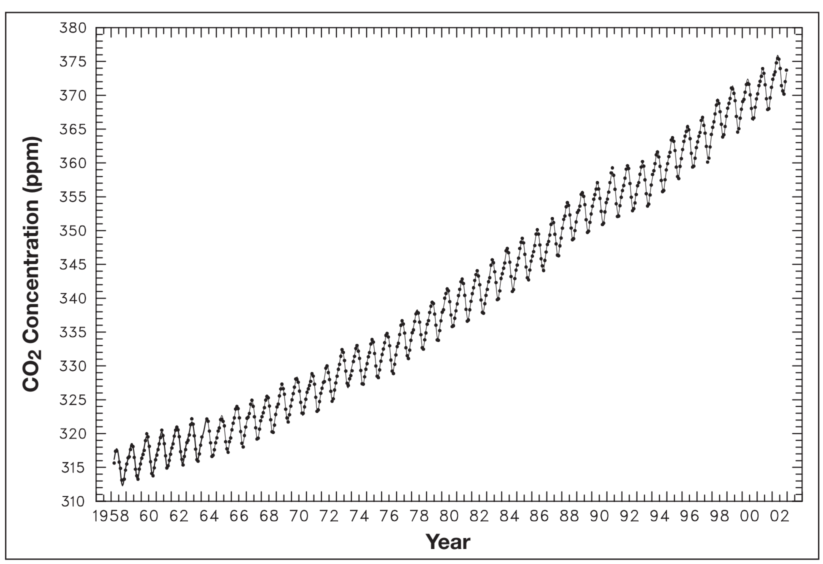


Figure 1. Atmospheric carbon dioxide monthly mean mixing ratios as observed by Tans and Keeling at Mauna Loa, Hawaii. Data prior to May 1974 are from the Scripps Institution of Oceanography, and data since May 1974 are from the National Oceanic and Atmospheric Administration (NOAA).

have impacts on Earth's climate. Prior to the late 1990s, space-based systems for global monitoring lacked the spatial, temporal, and spectral coverage necessary to provide observations with the accuracy and precision desired to interpret the interactions among these variables and their individual and combined contributions to global climate. Furthermore, modeling of these interactive processes did not represent them with sufficient accuracy to generate reliable predictions of the magnitude and timing of global climate change.

Overview

NASA uses space-, ground-, and aircraft-based measurement systems to provide the scientific basis for understanding the Earth system, especially its climate, weather, and natural hazards components. NASA contributes ongoing and near-term satellite missions, new missions under development, planned future missions, management and analysis of satellite and *in situ* data, and a continuing basic-research program focused on process studies, modeling, and data analysis. The space-based components of NASA's Earth science program provide a constellation of satellites to study Earth from space. Sustained observations allow researchers to monitor Earth's climate variables over time to determine trends; however, launching satellites alone is not sufficient. A comprehensive data and information system, a community of scientists performing research with the data acquired, and extensive ground and airborne campaigns are all important components. More than any other factor, the commitment to make Earth science data easily available to the research community is critical to mission success.

Satellites operating in a variety of orbits form the space component of NASA's Earth science program. No single orbit permits the gathering of complete information on Earth processes. For example, the low-inclination orbit of the Tropical Rainfall Measuring Mission (TRMM) was chosen specifically because TRMM was designed to study tropical rainfall and the associated release of energy that helps to power the global atmospheric circulation. High-inclination, polar-orbiting satellites are needed to observe phenomena that require relatively detailed observations on a routine basis, often from a constant solar-illumination angle. Geostationary satellites are needed to provide continuous monitoring of high-temporal-resolution processes; an international array of these platforms now provides coverage on a near-global basis. This coverage may be improved in the next few years by geostationary satellites with advanced instrumentation planned by NASA and its international partners.

Advances in observing and information technologies, research, and modeling are all required to fulfill NASA's long-term vision for Earth system prediction. The observing system of the future will continue to include satellites in a variety of orbits. These will include a 'sensorweb' of small, smart satellites in low Earth orbit, large-aperture sensors in geostationary orbits, and sentinel satellites at the Lagrangian points L1 and L2 (about 1.5 million kilometers from Earth) to provide synoptic day/night views of the entire globe from pole to pole. Onboard data processing and high-speed computing and communications will enable delivery of tailored information products from satellites direct to users at the cost of today's international telephone calls.

Earth Science Mission, Goals, and Objectives

NASA's Earth-Sun Exploration Division is currently in charge of NASA's Earth science program and plans its scientific and programmatic endeavors in accord with NASA's Vision and Mission, in the context of current scientific, societal, and national imperatives:

The NASA Vision:
To improve life here,
To extend life to there,
To find life beyond.

The NASA Mission:
To understand and protect our home planet,
To explore the universe and search for life,
To inspire the next generation of explorers.

The former Earth Science Enterprise (ESE) expanded the Earth-oriented parts of the NASA Vision and Mission to the following ESE mission statement:

> "To understand and protect our home planet by using our view from space to study the Earth system and improve prediction of Earth system change."

One of NASA's goals is: "Understand the Earth system and apply Earth system science to improve the prediction of climate, weather, and natural hazards," and among NASA's objectives within this goal are: "Understand how Earth is changing; better predict change and understand the consequences for life on Earth." These objectives are at the core of the Earth science mission and lead to the following fundamental question guiding scientific research and applications in NASA's Earth science program:

> "How is Earth changing, and what are the consequences for life on Earth?"

NASA's Earth Science Satellite Program: 1991–2004

The Earth Observing System (EOS)—consisting of a science segment, a data system, and a space segment made up of a series of polar-orbiting and low-inclination satellites for long-term global observations of the land surface, biosphere, solid Earth, atmosphere, and oceans—is the centerpiece of NASA's Earth science satellite program. In concert with EOS, the polar-orbiting and mid-inclination platforms from Europe, Japan, and NOAA form the basis for working with the Committee on Earth Observation Satellites (CEOS) to construct an Integrated Global Observing Strategy (IGOS). In combination, the programs from NASA, Japan, and the European Space Agency (ESA) establish an international Earth-observing capability covering all major Earth-system processes.

Table 1 identifies the NASA, other U.S., and international contributions of recent Earth observing satellites, beginning with the launch of the Upper Atmosphere Research Satellite (UARS) on September 12, 1991. Additional details on many of these satellite missions are presented later in this Handbook. EOS satellites carry two classes of instruments, both geared to overall NASA objectives. These two classes are: Facility Instruments, supplied by NASA in response to general mission requirements, and Principal Investigator (PI) Instruments, selected through a competitive process and aimed at the focused research interests of the selected investigators. The individual mission sections provide details on the science being accomplished and the high-level engineering specifications for the instruments now included in the program.

The program has a number of major elements other than the EOS spacecraft and instruments. These essential elements—Research Program, Earth Observing Program, EOS Data and Information System (EOSDIS), Applied Sciences Program, Education Program, Technology Program, International Cooperation, and Interagency Coordination—receive coverage in the next sections of this Handbook.

The data-collection segment of the program—EOS, Pathfinders, geostationary satellites, and aircraft- and ground-based programs—provides the comprehensive global observations necessary to understand how the processes that govern global change interact as part of the Earth system. With the help of the resultant increased knowledge, models are being developed to help predict future environmental change on local, regional, and global scales. For those who make observations of the Earth system and develop models of its operation, Earth system science involves the creation of interdisciplinary models that couple elements from formerly disparate sciences, such as terrestrial ecology and meteorology.

NASA's Earth Science Satellite Program: 2004 and Beyond

Future plans include a new generation of satellites in geostationary orbit and additional Pathfinder satellites addressing specific Earth science investigations. NASA has a Technology Program for developing a new generation of sensor technologies. These technologies will eventually migrate into future flight programs. The data-system aspects will continue throughout and beyond the lifetime of the EOS mission.

Several mission categories have been identified to provide critical Earth science measurements not provided by the current international constellation of satellites. NASA is pursuing collaborations with domestic and/or international partners in the following disciplines: Global change, global precipitation, solid-Earth topography, and ocean topography. Additional Earth System Science Pathfinder (ESSP) missions will be launched as particular observations are requested by the national and international science community, or as data gaps develop. The main driver behind this program is the need to provide focused missions in a more-expeditious manner, alleviating lengthy procurements. These small-to-moderate-sized satellites have highly focused objectives and obtain measurements that are not provided by other instrument suites.

EOS missions will provide high-spatial-resolution global information. The various orbits of these spacecraft will give Earth scientists a comprehensive, cohesive set of observations of Earth system processes, over a wide range of scales.

Research Program Focus Areas

NASA's Earth science research program is guided by the fundamental two-part question: "How is Earth changing, and what are the consequences for life on Earth?" This question leads to the following three-part quest for Earth system science: 1) to explore interactions among the major components of the Earth system—land, oceans, atmosphere, ice, and life; 2) to distinguish natural from human-induced causes of change; and 3) to understand and predict the consequences of change. NASA has established the following six science focus areas for these complex processes, along with Applied Sciences program elements for each focus area (in each focus area an Earth-Sun connection is implicit):

- Climate Variability and Change
- Atmospheric Composition
- Carbon Cycle, Ecosystems, and Biogeochemistry
- Water and Energy Cycles
- Weather
- Earth Surface and Interior

In each of these areas, NASA seeks the input of the Earth science community in government, in universities, and elsewhere to identify the scientific questions to be addressed and to define effective strategies to pursue the answers to those questions. NASA chartered the Solid Earth Science Working Group, led by a member of its external Earth System Science and Applications Advisory Committee (ESSAAC) and comprising experts from around the Nation, to lay out a course of research for the next two decades. The report of this group was the starting point for an Earth Surface and Interior science-focus area roadmap leading to a predictive capability over the next 10 years. Similarly, future contributions have been defined in other science focus areas. For example, the U.S. Weather Research Program's priorities are the basis for NASA's planning in the Weather science focus area.

The next challenge is to further integrate these six focus areas into a comprehensive understanding of the Earth system, represented by process models and coupled models. NASA will develop these models around scientific prediction questions for each focus area. The magnitude and scope of the fundamental question, mentioned above, are too large to allow a simple answer. A second tier of five questions provides a structure constituting the conceptual approach NASA is taking to improve our knowledge of the Earth system. These five questions define a pathway of 'variability, forcing, response, consequences, and prediction' that is taken to further enumerate a third tier of 24 more-specific questions which provide direction and focus to the program. The five second-tier and 24 third-tier questions, taken from the *NASA Earth Science Enterprise Strategy* (NASA 2003), are:

1) How is the global Earth system changing? *(Variability)*

- How are global precipitation, evaporation, and the cycling of water changing?
- How is the global ocean circulation varying on interannual, decadal, and longer time scales?
- How are global ecosystems changing?
- How is atmospheric composition changing?
- What changes are occurring in the mass of Earth's ice cover?
- How is Earth's surface being transformed by naturally occurring tectonic and climatic processes?

2) What are the primary forcings of the Earth system? *(Forcing)*

- What trends in atmospheric constituents and solar radiation are driving global climate?
- What changes are occurring in global land cover and land use, and what are their causes?
- What are the motions of Earth's interior, and how do they directly impact our environment?

3) How does the Earth system respond to natural and human-induced changes? *(Response)*

- What are the effects of clouds and surface hydrologic processes on Earth's climate?
- How do ecosystems, land cover, and biogeochemical cycles respond to and affect global environmental change?
- How can climate variations induce changes in the global ocean circulation?
- How do atmospheric trace constituents respond to and affect global environmental change?
- How is global sea level affected by natural variability and human-induced change in the Earth system?

4) What are the consequences of change in the Earth system for human civilization? *(Consequences)*

- How are variations in local weather, precipitation, and water resources related to global climate variation?
- What are the consequences of land cover and land use change for human societies and the sustainability of ecosystems?
- What are the consequences of climate change and increased human activities for coastal regions?
- What are the effects of global atmospheric chemical and climate changes on regional air quality?

5) How will the Earth system change in the future and how can we improve predictions through advances in remote sensing observations, data assimilation, and modeling? *(Prediction; the six questions correspond to the six science focus areas.)*

- How can weather forecast duration and reliability be improved?
- How can predictions of climate variability and change be improved?
- How will future changes in atmospheric composition affect ozone, climate, and global air quality?
- How will carbon cycle dynamics and terrestrial and marine ecosystems change in the future?
- How will water cycle dynamics change in the future?
- How can our knowledge of Earth surface change be used to predict and mitigate natural disasters?

The following strategic principles govern the formulation and implementation of the Earth science research program:

- Choose scientific questions for which NASA technology and remote sensing can make a defining contribution;

- Pursue answers to these questions using an 'end-to-end' systems approach that includes observation, research and data analysis, modeling, and scientific assessment in collaboration with our partners;

- Engage the broader Earth science community throughout the process, from question formulation to the final release of findings to decision makers and the public;

- Identify and generate a specific set of validated climate-data records in collaboration with the science community and our domestic and international partners;

- Create data-assimilation capabilities for available diverse data types;

- Develop computational modeling capabilities for research focus areas;

- Participate in national and international scientific assessments of the state and directions of Earth system change in support of policy and economic decision-making processes, aligning our science priorities with those of major national imperatives;

- Establish and maintain critical linkages to NASA's space science program in areas such as the Sun-Earth Connection theme, Living with a Star program, astrobiology, and comparative planetology.

The six science focus areas are interrelated and must eventually be integrated to arrive at a fully interactive and realistic Earth system representation. For each science focus area, NASA has developed a decadal roadmap guiding investments and describing how we intend to achieve the outcomes listed above. These roadmaps show the science products being produced today and those we believe we can deliver, or enable others to deliver, 10 years from now. In between, the roadmaps show the steps required to get there and the needed observation and modeling capabilities. Fully detailed roadmaps for each science focus area can be accessed at: earth.nasa.gov/roadmaps.

A detailed discussion of the Earth science research program—and of the associated Programs on Observation and Information Management, Advanced Technology, Applications, and Education—can be accessed in the document *Earth Science Enterprise Strategy* (NASA 2003) and other related documents, at: science.hq.nasa.gov/strategy/index.html

Science Investigations

In 1988, NASA issued an Announcement of Opportunity (AO) for the selection of instruments, science teams, and interdisciplinary investigation teams in support of EOS. In response 455 proposals were received, and in 1989 NASA announced the selection of 30 instruments and their instrument teams plus 28 Interdisciplinary Science (IDS) Investigation teams. Altogether, 551 individuals became members of EOS teams. The instrument teams were in charge of algorithm development to convert the measurements from each individual instrument to the desired geophysical parameters. The IDS teams were selected to conduct basic research, develop methods and models for analysis of EOS observations, develop and refine models of Earth system processes, and forge new alliances among scientific disciplines fostering a unique perspective into how Earth functions as an integrated system. As the program evolved over the years a number of IDS investigations were added, and some were discontinued.

Starting in 1995, NASA has issued many NASA Research Announcements (NRAs) to add new investigations and augment the EOS instrument and interdisciplinary science teams. In each case, selections were made based on peer reviews done by scientific experts from academia and government.

A number of groups and programs contribute to the IDS investigations. For example, the EOS instrument-science teams help define the scientific requirements for their respective instruments and generate the algorithms that are used to process the data into useful data products used in the investigations. Further, the science teams are responsible for validation of the algorithms and data products they produce. Listings of instrument-science teams can be found at: eospso.gsfc.nasa.gov/directory/instrument/. Listings of Algorithm Theoretical Basis Documents (ATBD) can be found at: eos.gsfc.nasa.gov/eos_homepage/for_scientists/atbd/.

As described at the beginning of this Section, NASA has identified six science focus areas that generally encompass individual discipline components of the Earth system. However, NASA stresses the importance of interdisciplinary science and emphasizes that the implementation of the IDS program builds on the strength of the existing Earth science disciplines.

Many of the important scientific questions being studied by EOS scientists require analyses by interdisciplinary teams using data and information from multiple EOS and international instruments and *in situ* observations. The IDS investigation teams bring together highly talented experts from diverse fields to tackle specific areas of uncertainty regarding the functioning of the Earth as a coupled system. All investigations exploit the EOS data, with research results being made available through the

EOS Data and Information System (EOSDIS) to enhance broad participation by the science community at large.

Another route for scientists to enter into the EOS community is through the New Investigator Program (NIP) in Earth Science, which is directed at scientists near the beginning of their careers (usually within five years of obtaining a Ph.D. degree). The NIP was established in 1996 to encourage Earth system science research and education by scientists and engineers at the early stage of their professional careers. The program, designed for investigators in Earth system science and applications at academic institutions and non-profit organizations, emphasizes the early development of professional careers of these individuals as both researchers and educators. The program encourages scientists and engineers to develop a broader sense of responsibility for effectively contributing to the improvement of science education and the public's science literacy. For this, it provides an opportunity for the investigators to develop partnerships and/or enhance their skills, knowledge, and ability to communicate the excitement, challenge, methods, and results of their work to teachers, students, and the public. An NIP Announcement is issued about every one-and-a-half years. On March 31, 2004, NASA announced the selection of 31 proposals, from 126 submitted in response to an NRA to conduct research and education activities under NIP.

The roadmap and focus for both IDS and NIP investigations are encompassed in the fundamental question and associated hierarchy of science questions, set forth in the *Earth Science Enterprise Strategy* (NASA 2003) and discussed earlier in this Section.

NASA's Role in U.S. Climate Change Science and Technology Programs

In February 2002, the President created a new Cabinet-level management structure, the Committee on Climate Change Science and Technology Integration, to oversee the full scope of federal climate-change research and technology development. Within this structure, CCSP integrates research and related activities sponsored by the U.S. Departments of Agriculture, Commerce, Defense, Energy, Health and Human Services, Interior, State, and Transportation, as well as the Environmental Protection Agency, NASA, National Science Foundation, Smithsonian Institution, U.S. Agency for International Development, Office of Science and Technology Policy, and Office of Management and Budget.

The Director of the Climate Change Science Program Office (CCSPO) is the Assistant Secretary of Commerce for Oceans and Atmosphere. CCSP encompasses CCRI and USGCRP. CCSPO has produced a vision document and strategic plan that can be accessed at www.climatescience.gov. NASA's Earth system science research paradigm, science focus areas, and program elements are well aligned with corresponding elements of CCSP.

References

NASA, 2003: *Earth Science Enterprise Strategy, October 2003*. NASA Headquarters, Washington, DC, 94 pp. [Available online at: science.hq.nasa.gov/strategy/index.html.]

NASA, 2000: *Understanding Earth System Change: NASA's Earth Science Enterprise Research Strategy for 2000-2010, December 2000*. NASA Headquarters, Washington, DC, 55 pp. [Available online at: earth.nasa.gov/visions/researchstrat/.]

NASA Earth System Science and Applications Advisory Committee (ESSAAC), 1994–Present: *Agenda and Minutes of Biannual Meetings.* [Available online at: science.hq.nasa.gov/.]

Climate Change Science Program and Subcommittee on Global Change Research, 2003: *Strategic Plan for the U.S. Climate Change Science Program, July 2003*. Climate Change Science Program Office, Washington, DC, 203 pp. [Available online at: www.climatescience.gov.]

NASA Earth Observing System:
eospso.gsfc.nasa.gov

Launch	Satellite	Mission Objectives
1991	**UARS**	Measure upper atmospheric characteristics to examine stratospheric and mesospheric chemistry and dynamic processes.
1991-2000	**NASA Shuttle Missions**	Measure atmospheric ozone (SSBUV), atmospheric and solar dynamics (ATLAS), atmospheric aerosols (LITE), and surface height (SLA), through a series of Shuttle-based experiments. Shuttle Radar Topography Mission (SRTM), including X-SAR, SIR-C, and GPS instruments, was launched February 11, 2000 (joint with Germany and Italy).
1991	**Meteor-3/TOMS**	Monitor and map atmospheric ozone (joint with Russia).
1992	**TOPEX/Poseidon**	Monitor changes in sea-level height to study ocean circulation (joint with France).
1996	**Earth Probe/TOMS**	Monitor and map atmospheric ozone. Together with TOMS aboard Nimbus-7 (launched 1978) and Meteor-3 (launched 1991), the Earth Probe TOMS provides a data set of daily ozone for over two decades.
1997	**Orbview-2/SeaWiFS**	Monitor ocean productivity (an ocean-color data purchase).
1997	**TRMM**	Measure precipitation, clouds, lightning, and radiation processes over tropical regions (joint with Japan). Data from CERES instruments on Terra, Aqua, and TRMM extend the long-term radiation-budget record that began with the three-satellite configurations of ERBS (launched 1984), NOAA-9, and NOAA-10, each carrying the Earth Radiation Budget Experiment (ERBE) instrument.
1999	**Landsat 7**	Monitor the land surface through high-spatial-resolution visible and infrared measurements (joint with USGS).
1999	**QuikSCAT**	Measure ocean surface wind vectors, with the SeaWinds instrument.
1999	**Terra**	Collect global data on the state of the atmosphere, land, and oceans, and their interactions with solar radiation and with one another (includes Canadian and Japanese instruments). See TRMM entry for the radiation-budget measurements with the CERES instruments on Terra, Aqua, and TRMM.
1999	**ACRIMSAT**	Monitor total solar irradiance.
2000	**CHAMP**	1) Map Earth's gravity field and its temporal variations; 2) map Earth's global magnetic field and its temporal variations; 3) perform atmospheric/ionospheric sounding (cooperative with Germany).
2000	**EO-1**	Collect data to allow paired scene comparisons between EO-1 Advanced Land Imager (ALI) and Landsat 7 Enhanced Thematic Mapper Plus (ETM+).
2000	**SAC-C**	Perform various environmental, magnetic, navigation, space radiation, and other experiments. (Cooperative mission with Argentina, with contributions from Brazil, Denmark, France, and Italy).
2001	**Jason**	Monitor ocean height to study ocean circulation (joint with France).
2001	**Meteor-3M/ SAGE III**	Retrieve global profiles of atmospheric aerosols, ozone, water vapor, other trace gases, temperature and pressure in the mesosphere, stratosphere, and troposphere (joint with Russia).

Table 1. NASA Earth Science Satellite Program, 1991–2010.

Launch	Satellite	Mission Objectives
2002	**GRACE**	Measure Earth's gravity field and its variations with time (joint with Germany).
2002	**Aqua**	Monitor atmospheric, land, ocean, and ice variables for improved understanding of the Earth's water cycle and improved understanding of the intricacies of the climate system (includes Brazilian and Japanese instruments). See TRMM entry for the radiation-budget measurements with the CERES instruments on Terra, Aqua, and TRMM.
2002	**ADEOS II (Midori II - Japan)**	Monitor ozone, aerosols, atmospheric temperature, winds, water vapor, SST, energy budget, clouds, snow and ice, ocean currents, ocean color/biology, from visible-to-thermal-infrared radiance/reflectance, microwave imaging, and scatterometry (includes French and U.S. instruments).
2003	**ICESat**	Measure elements of ice-sheet mass balance, cloud-top and land-surface topography, and vertical profiles of aerosol and cloud properties.
2003	**SORCE**	Measure the total and spectral solar irradiance incident at the top of Earth's atmosphere.
2004	**Aura**	Measure atmospheric chemical composition; tropospheric/stratospheric exchange of energy and chemicals; chemistry-climate interactions; air quality (includes joint Netherlands/Finland and joint U.K./U.S. instruments).
2006	**CALIPSO**	Measure the vertical distribution of clouds and aerosols (joint with France).
2006	**CloudSat**	Measure cloud characteristics, to increase the understanding of the role of optically thick clouds in Earth's radiation budget (joint with Canada).
Planned		
~2008	**Glory***	Determine atmospheric aerosol properties from the polarization of backscattered solar radiation. Also, measure total solar irradiance.
~2008	**OSTM***	Determine ocean surface topography to study ocean circulation and its environmental applications (follow-on to Jason; cooperative with France, EUMETSAT, and NOAA).
~2008	**OCO**	Provide space-based observations of atmospheric carbon dioxide, the principal anthropogenic driver of climate change.
~2008	**NPP**	Extend key measurements in support of long-term monitoring of climate trends and global biological activity (joint NOAA-DoD-NASA mission). NPP extends the measurement series being initiated with EOS Terra and Aqua by providing a bridge between NASA's EOS missions and NPOESS, scheduled to replace the separate NOAA and DoD operational systems in about 2010.
TBD	**LDCM***	Extend the Landsat record of multispectral, 30-m resolution, seasonal, global coverage of Earth's land surface (joint with USGS).
~2009	**Aquarius***	Measure global sea surface salinity (cooperative mission with Argentina).

Table 1. NASA Earth Science Satellite Program, 1991–2010 *(cont.).*

Launch	Satellite	Mission Objectives
~2008	**DSCOVR***	Continuously observe the Earth from the Sun-Earth libration point, L1 (1,500,000 km away from Earth) (cooperative project with NASA's space science program).
~2010	**GPM***	Monitor precipitation globally (joint with Japan and other international partners, building on the success of TRMM).
POES Series Operational#		Provide global coverage of numerous atmospheric and surface parameters for weather forecasting and meteorological research, as well as data collection, search and rescue, and environmental monitoring.
GOES Series Operational#		Provide weather imagery and quantitative sounding data to support weather forecasting, severe-storm tracking, and meteorological research, disaster management, public health, and aviation safety.

* Mission is currently under study; hence, the information is preliminary.

NASA is responsible for the integration and launch of NOAA satellites.

Table 1. NASA Earth Science Satellite Program, 1991–2010 *(cont.)*.

Earth Observing Program

Introduction

Planning for the Earth Observing System (EOS) Program began in the early 1980s, and an Announcement of Opportunity (AO) for the selection of instruments and science teams was issued in 1988. 458 proposals were received in response to the AO. Early in 1990, NASA announced the selection of 30 instruments to be developed for EOS. The corresponding science-team members were also identified, as were the members of 29 Interdisciplinary Science (IDS) teams.

EOS was recognized in 1990 as part of the Presidential initiative, receiving its 'new start' from Congress in October. The EOS Program was funded under a continuing resolution, and ramped up to its full funding with the approval of the FY 91 budget in January 1991. A NASA research announcement (NRA) for the selection of new investigations, instrument teams, and young investigators was issued in 1995, and 309 proposals were received in response. On July 1, 1996, NASA announced the selection of team members for 5 instrument teams, 31 IDS Teams, and 21 New Investigators. An NRA was issued in 1997, resulting in the establishment of Landsat 7 and Jason Science Teams. NRAs issued in 1998 resulted in the augmentation of the Tropical Rainfall Measuring Mission (TRMM) Science Team and the selection of members of the Instrument Incubator Program (IIP) and the New Investigator Program (NIP), as well as the selection of members of the New Millennium Program/Earth Observing-1 (NMP/EO-1) Science Team. The Ozone Monitoring Instrument (OMI) on Aura is a contribution of the Netherlands' Agency for Aerospace Programs (Nederlands Instituut voor Vliegtuigontwikkeling en Ruimtevaart, or NIVR) in collaboration with the Finnish Meteorological Institute (FMI). A Netherlands/Finnish Instrument Science Team was formed in 1999, and, following the issuance of an NRA, a U.S. OMI Instrument Science Team was formed in 2000.

Additional NRAs led to the following sequence of NASA announcements:

September 8, 2003—Selection of 24 proposals, from 68 submissions, to form a Science Team for the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Preparatory Project (NPP) satellite.

October 29, 2003—Selection of 59 proposals, from 348 submissions, to perform IDS research.

December 22, 2003—Selection of 192 proposals, from 566 submissions, to reconstitute Science Teams to perform Earth system science research using data and products from Terra, Aqua, and the Active Cavity Radiometer Irradiance Monitor Satellite (ACRIMSAT).

March 31, 2004—Selection of 31 proposals, from 126 submissions, to conduct research and education activities under NIP.

The names of the selected investigations and their principal investigators can be found at: research.hq.nasa.gov/code_y/archive.cfm.

EOS Science Objectives

The EOS program was designed to initiate a new era of integrated global observations intended to advance our understanding of the entire Earth system on a global scale through developing a deeper understanding of the components of that system, their interactions, and how Earth is changing. The extent of Earth system changes, e.g., the change in average temperature and the time scale over which it will occur, is presently unknown. Causes can be either natural or human-induced. Both must be understood to determine how to alter human behavior appropriately to avoid climate changes that prove most detrimental to the environment. The regional consequences of climate change, e.g., changes in precipitation patterns, length of growing seasons, severity of storms, and change of sea level, must be understood to determine which aspects of climate change are most harmful, and how to adapt to those changes that the human species cannot avoid.

The EOS Investigators Working Group (IWG) defined the following seven science and policy priorities for EOS observations, based on scientific recommendations by national and international programs such as the Intergovernmental Panel on Climate Change (IPCC) and the Committee on the Environment and Natural Resources (CENR):

1) **Radiation, Clouds, Water Vapor, and Precipitation**
   Cloud formation, dissipation, and radiative properties, all of which influence response of the atmosphere to greenhouse forcing, plus water vapor and precipitation and their roles in climate and global change.

2) **Oceans**
   Exchange of energy, water, and chemicals between the ocean and atmosphere, and between the upper layers of the ocean and deep ocean (includes sea ice and formation of bottom water).

3) **Greenhouse Gases**
   Links to the hydrologic cycle and ecosystems, transformations of greenhouse gases in the atmosphere, and interactions inducing climate change.

4) **Land-Surface Hydrology and Ecosystem Processes**
   Improved estimates of runoff over the land surface and into the oceans, sources and sinks of greenhouse gases, exchange of moisture and energy between the land surface and atmosphere, and changes in land cover.

5) **Glaciers, Sea Ice, and Ice Sheets**
   Changes in the global ice cover and predictions of sea-level change and global water balance.

6) **Ozone and Stratospheric Chemistry**
   Chemical reactions, solar-atmosphere relations, and sources and sinks of radiatively important gases.

7) **Volcanoes and Climate Effects of Aerosols**
   Volcanoes and their role in climatic change.

These seven science priorities, defined by IWG in the *EOS Science Plan* (King *et al.*, 1999, and Greenstone and King, 1999), are in full accord with the six science focus areas and with the fundamental question and its hierarchy of five pathway questions and 24 subsidiary questions set forth in the *Earth Science Enterprise Strategy* (NASA 2003) and discussed in the preceding section of this Handbook.

Prior to the receipt of a new start from Congress in 1990, the IWG—consisting of all selected IDS Principal Investigators (PIs) and Co-PIs; Instrument PIs and Co-PIs; and Facility Team Leaders and Team Members—began meeting every nine months or so to discuss the scientific objectives of the program and other matters in coordination with the national and international community. At that time Science Working Groups for the major EOS satellite missions, certain Functional Panels, and Panels for a number of scientific disciplines were established.

The EOS Program provides resources to support the scientific research required to turn satellite measurements into science data products for inclusion in, or comparison with, model results. Specifically, EOS has supported scientific investigations through IDS investigations, Instrument Teams, and NIP, all selected through a competitive process. Many of the IDS investigations centered on development and refinement of integrated Earth system models, to be used with EOS instrument observations to advance the understanding of the Earth as a system. NASA generally issues NRAs every 18 months-to-two years to allow broader participation in the EOS Program by members of the Earth-science community.

Prior to launch, EOS Instrument Teams help define the scientific requirements for their respective instruments and generate the algorithms that will be used to process the data into useful data products. (See the Algorithm Theoretical Basis Documents [ATBDs] for an in-depth presentation of the algorithms. Each ATBD can be downloaded at: eos.nasa.gov/eos_homepage/for_scientists/atbd/.) After launch, the Instrument Teams maintain and refine the algorithms, analyze the data, and undertake validation studies.

EOS investigations are intended to characterize the Earth system as an integrated whole, while also quantifying the regional processes that govern it. EOS Research was based initially on the existing sources of ground- and space-based observations and has continued through and beyond the launch of the EOS satellites. Efforts to understand these Earth system elements will shed light on how Earth functions as a coupled and integrated system, how it responds to human-induced perturbations, and how this response manifests itself in the continuing course of global climate change. A discussion of the different types of products made available by the EOS Data and Information System (EOSDIS) is provided in the next section.

The sections on Interagency Coordination and Applied Sciences describe the roles played by other Federal agencies, in cooperation with NASA, to make and analyze observations of Earth. Later sections detail the missions and instrument suites that fit into the Integrated Global Observing Strategy (IGOS). Payload configurations and launch dates of planned future missions are always subject to change.

EOS Program Revisions

Starting in 1991, and continuing over the decade that followed, there was a series of major revisions of the EOS Program, generally prompted by substantial budget reductions. Readers interested in the details of these revisions are referred to the *1999 EOS Reference Handbook* (Greenstone and King, 1999, pp. 17–19). The various revisions set the tone for a new strategy for planning future missions—one more flexible, more responsive to science needs, and more accommodating of partnerships.

Pre-EOS Satellites That Strongly Influenced the EOS Program

During the period 1964–1986 twelve satellites were launched that strongly influenced EOS. The Nimbus program consisted of seven 3-axis-stabilized satellites, in sun-synchronous orbits, that tested for the first time more than 40 instruments/systems, including cameras, visible/infrared/microwave imaging radiometers, infrared/microwave atmospheric sounders, radiation-budget instruments, sensors for measuring ozone and other trace constituents in the troposphere/stratosphere, direct readout systems, and data-collection and platform-location systems. Many of these instruments/systems were forerunners of advanced instruments/systems that are flying (or scheduled to fly) on current and future EOS/Earth System Science Pathfinder (ESSP)/NMP missions and National Oceanic and Atmospheric Administration (NOAA) operational satellites.

The Applications Technology Satellite (ATS) program launched two satellites into geosynchronous orbits in December 1966 (ATS-1) and November 1967 (ATS-3). ATS-1 carried a Spin Scan Cloud Camera (SSCC), and ATS-3 carried a Multicolor Spin Scan Cloud Camera (MSSCC). These sensors were forerunners of the visible/infrared imagers currently flying on Geostationary Operational Environmental Satellites (GOES).

The Earth Radiation Budget Satellite (ERBS) was deployed in orbit from the Space Shuttle Challenger, launched on October 5, 1984. ERBS was part of a three-satellite experiment, the two other satellites being NOAA-9, launched on December 12, 1984, and NOAA-10, launched on September 17, 1986. Each of these satellites carried an Earth Radiation Budget Experiment (ERBE) instrument to investigate how energy from the Sun is reflected from or absorbed and re-emitted by Earth. This three-satellite experiment was the forerunner of the subsequent more-advanced radiation budget measurements made by the Clouds and the Earth's Radiant Energy System (CERES) instruments flying on TRMM, Terra and Aqua.

Status of the Program in 2006

Mission schedules as of 2006 are illustrated in Figures 2a, 2b and Table 2, including EOS, NMP, and ESSP missions. The resulting data-communication requirements are shown in Table 3. Note that PM-1 was renamed Aqua, and CHEM was renamed Aura since publication of the 1999 Handbook.

More information about the condition of Earth can be obtained from coordinated observations from several satellites than would be possible from the sum of uncoordinated observations. Aqua, launched on May 4, 2002, Aura, launched on July 15, 2004, and Polarization and Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar (PARASOL-France), launched on December 18, 2004, are flying in nearly the same orbit, in a line with Aqua in the lead and Aura in the rear. These three will be joined by CloudSat and the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO—a joint effort with France), both launched on April 28, 2006; and eventually by the Orbiting Carbon Observatory (OCO), scheduled for launch in 2008. Since all six of these satellites will fly in a coordinated fashion in essentially the same orbit, the set is referred to as a constellation, or, alternatively, a formation. Furthermore, since this constellation is composed of missions with equator crossings in the early afternoon, around 1:30 p.m. local time (and in the middle of the night, around 1:30 a.m.), it is referred to as the Afternoon Constellation or, because of the prominent positions of Aqua and Aura, as the 'A-Train' (see Figure 3). Flying these satellites in formation facilitates the integration of their data on clouds, aerosols, and atmospheric properties and chemical composition into greatly enriched scientific information products. In many ways this type of constellation acts as a giant virtual observatory, and it points the way toward the development—with national and international partnerships—of the space-based component of a future Earth system model suite. Such a suite would integrate remote sensing, suborbital, and *in situ* measurements with accurate predictive capabilities, and ultimately enhance the prediction of Earth system change and improve life on Earth in this century (NASA 2003).

The French PARASOL mission carries a polarimeter (Polarization and Directionality of the Earth's Reflectances—POLDER), which provides unique information to the A-Train data mix. POLDER is a camera with nine spectral channels, of which three (at 443, 670, and 865 nm) have three polarization filters that are moved sequentially in front of the aperture, for a POLDER total of 15 channels. Aerosols, cloud particles, and certain land-surface types strongly polarize reflected light; and POLDER is able to obtain additional information on aerosol types and cloud particle size distributions from its polarization information. POLDER was also flown on the Japanese Advanced Earth Observation Satellite (ADEOS) II satellite, launched in December 2002 and operational until October 2003.

Another constellation, consisting of Landsat 7, EO-1, Satellite for Scientific Applications (SAC-C, with Argentina), and Terra—all flying in the same orbit with equator crossings in mid-morning around 10:30 a.m. local time (and around 10:30 p.m.)—is called the 'Morning Constellation' (see Figure 4). Flying these satellites in formation facilitates the integration of their data on vegetation and land-surface cover, surface temperature and processes, ocean characteristics, and cloud properties. Further, having the Moderate Resolution Imaging Spectroradiometer (MODIS) and CERES instruments on both the Terra and Aqua satellites provides scientists an opportunity to examine aspects of the diurnal cycle of the many parameters being measured by these instruments.

More details concerning the status of EOS missions and related Earth Science Programs appear later in this Handbook, in sections on the individual missions.

Implementation of the Earth Science Program

NASA has developed a strategy for exploring our home planet over a period of 10 years and beyond to develop a scientific understanding of the Earth system and its response to enable improved prediction of climate, weather, and natural hazards for present and future generations [*Earth Science Enterprise Strategy* (NASA 2003)].

NASA's Office of Earth Science, in consultation with its Earth System Science and Applications Advisory Committee (ESSAAC) and selected members of the broader Earth science community, prepared the document *Understanding Earth System Change: NASA's Earth Science Enterprise Research Strategy for 2000–2010* (NASA 2000), which also incorporates comments from a formal review by the National Academy of Sciences. This Research Strategy is one of a family of strategy documents being published to guide NASA's Earth science program for the next decade and beyond. The full set of planning documents can be obtained at: earth.nasa.gov/visions/.

Concurrent with the development of these plans is a longer-term effort to provide a vision for NASA's activities over the time period from 2010 to 2025. The longer-term broader-scale effort is designed to integrate more completely the technology, research, and applied science goals of NASA's Earth science program in a way that will allow for detailed end-to-end planning such that the scientifically and societally important questions posed can be answered, in particular with technological approaches specifically developed for that purpose. The resulting information will be provided to the scientific community and disseminated to the broader public through collaboration between NASA and its partners in the public and private sectors [*Earth Science Enterprise Strategy* (NASA 2003)].

Contributions of NASA to National Objectives

In pursuit of U.S. policy relative to global change, NASA undertakes observations from space and performs interdisciplinary science studies to interpret and apply these observations. Integrated and conceptual models, substantiated by space-based observations, have already provided policymakers with a firm basis for making sound environmental policy decisions related to substances that deplete the ozone layer, e.g., the Montreal Protocol on Substances that Deplete the Ozone Layer, adopted in 1987, and subsequent protocols. In the EOS era, the corresponding challenges include prediction of El Niño events, the implications of increased emissions of greenhouse gases for global warming, and impacts of land-cover change on the carbon budget, biodiversity, and agricultural productivity. Fuller discussion of these challenges is found in the *Earth Science Enterprise Strategy* (NASA 2003) and the *EOS Science Plan* (King *et al.*, 1999, and Greenstone and King, 1999).

A basic question relevant to policy decisions concerns the issue of whether changes now being observed throughout the world are systematic (relatively persistent long-term changes) or more oscillatory. Another basic question concerns how much of the change is tied to human impacts versus being part of normal climate variability. Further, if the changes are systematic, are they sufficiently significant in impact to warrant action by policymakers? Do we know well enough whether the observed changes are attributable to human activities? Are appropriate technological alternatives or restrictions on human activities available to mitigate the changes or their impacts, and is it reasonable to impose such restrictions? Are the consequences of imposing restrictions more damaging to our quality of life, e.g., because of major disruptions in the world's economy, than the anticipated changes in the global climate system?

The physical-modeling and data-gathering and analysis activities of the EOS Program are intended to make a major contribution to establishing the distinction between natural variability in the Earth system and changes that are introduced by human activities. The findings of NASA-supported scientists in the U.S. and their counterparts around the world provide valuable information to decision makers as they consider intervention strategies to mitigate undesirable changes.

NASA offers a new perspective on the functioning of planet Earth through coordinated, long-term, space-based and *in situ* observations, and a program of interdisciplinary research addressing priority issues of Earth system science. Following the EOS mandate from the Administration and Congress in 1990, NASA has placed itself at the forefront of Earth observing satellite technology development and data management. The improved measurement and modeling capabilities that result directly support the U.S. and international global-change-research programs, and reinforce the U.S. position as a world leader in space-based remote sensing.

EOS Data Quality: Calibration and Validation

Data quality for EOS is sought and checked through comprehensive calibration and validation programs. The primary objectives of these two programs are to characterize and document the accuracy and precision of EOS observations and derived geophysical and biophysical products over all relevant temporal and spatial scales. More specifically, these programs provide, respectively: 1) radiometric calibration and characterization of EOS instruments, and 2) validation of the observations and state variables, fluxes, and parameters derived directly from EOS observations, or in conjunction with data assimilation methods and integrated Earth system models. These programs involve hundreds of scientists and engineers around the world and are supported by the EOS Calibration and Validation Scientists, both of whom are part of the EOS Project Science Office, NASA Goddard Space Flight Center.

Calibration Program

In order to achieve the EOS goal of understanding the Earth system, EOS produces time series of satellite data sets from multiple instruments on multiple platforms averaged over different geographic regions, from local to global. The correct interpretation of scientific information from these data sets requires the ability to discriminate between satellite-instrument on-orbit changes and changes in Earth variables being monitored. The ability to make this discrimination on a pre-launch, post-launch, inter-instrument, and inter-platform basis crucially depends on the calibration of the instruments with respect to a set of recognized physical standards or processes and on the careful characterization of instrument performance at the subsystem and system levels.

In EOS, calibration is the set of operations or processes used to determine the relationship between satellite instrument output values (i.e., voltages or counts) and corresponding known values of a standard, expressed in Systeme Internationale (SI) units. Characterization is the set of operations or processes used to quantitatively understand the operation of an instrument and its response as a function of the gamut of operating and viewing conditions experienced by the instrument on-orbit. The complete calibration of an EOS instrument requires and implies that the instrument be well characterized. EOS instrument calibration and characterization are performed both pre-flight and on-orbit.

There are three types of radiometric calibration activities currently being conducted as part of the EOS Calibration Program: 1) laboratory calibration prior to launch, 2) in-flight calibration with onboard calibrators, and 3) vicarious calibration after launch.

1) Laboratory calibration activities focus on calibration of individual instruments with traceability to radiometric standards accepted by the national and international metrology community and implemented by organizations such as the U.S. National Institute of Standards and Technology (NIST). These activities also include the intercalibration of instruments that operate in the same region of the electromagnetic spectrum and that measure similar characteristics of the Earth system. For example, transfer radiometers have been used in round-robin intercomparisons that enable the transfer of metrology scales, maintained at national standards laboratories, to surface-imaging instruments such as the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), MODIS, and the Multi-angle Imaging SpectroRadiometer (MISR) on the Terra satellite. Preliminary results of a round-robin aperture-area comparison for exo-atmospheric solar irradiance have been reported by Johnson *et al.* (2003). The goal of this comparison was to quantify the relative differences in measurements of aperture area made by institutions involved in the on-orbit measurement of total solar irradiance and those made by NIST. Data on sets of six apertures from two institutions, referred to as Lab A and Lab B, were received, and the results are shown in Figure 5. The average percent bias for Laboratory A is 0.013%, and the average percent bias for Laboratory B is 0.065%. These equate to differences in total solar irradiance measurements of 0.18 W/m^2 and 0.89 W/m^2 for an assumed total solar irradiance value of 1366.3 W/m^2. Additional aperture-area comparisons are expected in the future, followed by publication of the carefully analyzed and interpreted results in a refereed publication.

2) In-flight calibration utilizes calibration lamps, reference panels with known reflectivity/emissivity, deep space, and ratioing radiometers.

3) Vicarious methods include the use of bright and dark target scenes on Earth, coincident sub-orbital flights of well-calibrated spectroradiometers over well-characterized Earth surfaces, and the use of the moon as a stable reference target that is characterized from high-spectral-and-spatial-resolution measurements made from ground-based observatories over the libration cycle of the moon.

The key components of the EOS Calibration Program are:

Pre-flight EOS Instrument Calibration
- Instrument Calibration Plans
- Calibration Peer Reviews
- Radiometric Measurement Comparisons
- EOS Calibration Panel
- Artifact Round-robins

Post-launch EOS Instrument Calibration
- On-orbit Platform Maneuvers, e.g., calibration attitude maneuvers
- The USGS Lunar Radiometric Measurement Program
- Level 1B Validation, e.g., vicarious calibration campaigns

Current information concerning the EOS Calibration Program is available at: eos.nasa.gov/calibration/.

Launch	Spacecraft	Instrument Complement	See Note(s)
1991	Meteor-3† *(Russia)*/TOMS	TOMS	1
1991	UARS	ACRIM, CLAES, HALOE, HRDI, *ISAMS (U.K.),* MLS, PEM, SOLSTICE, SUSIM, *WINDII (C, F)*	1
1992	TOPEX/Poseidon† *(France)*	ALT, *DORIS (F),* GPSDR, LRA, *Poseidon-1 (F),* TMR	1
1996	EP/TOMS	TOMS	1
1996	ADEOS (Midori)† *(Japan)*	NSCAT, TOMS	1
1997	Orbview-2† *(data buy)*	SeaWiFS	2
1997	TRMM *(U.S./Japan)*	CERES, LIS, *PR (J)*, TMI, VIRS	3
1999	Landsat 7	ETM+	
1999	QuikSCAT	SeaWinds	
1999	Terra	*ASTER (J)*, CERES (2), MISR, MODIS, *MOPITT (C)*	4, 5
1999	ACRIMSAT	ACRIM 3	
2000	CHAMP† *(Germany)*	*ACC (G)*, *DIDM (G),* GPS, *LRR (G), OVM/FGM (G)*	
2000	EO-1	ALI, Atmospheric Corrector, Hyperion	6
2000	SAC-C† *(Argentina)*	*DCS (A),* GOLPE, *HRTC (A), HCS (A)*, *ICARE (F), INES (I), ISTI (I), MMP (D), MMRS (A),* SHM, *[System Testing (B)], Whale Tracker Exp. (A)*	7
2001	Jason-1† *(France)*	*DORIS (F),* JMR, LRA, TRSR, *Poseidon-2 (F)*	
2001	Meteor-3M† *(Russia)* /SAGE III	SAGE III	
2002	GRACE† *(U.S./Germany)*	GPS, KBR, *SuperStar (U.S./F)*	8
2002	Aqua	AIRS, *AMSR-E (J)*, AMSU-A, CERES (2), *HSB (B)*, MODIS	4
2002	ADEOS II (Midori II)† *(Japan)*	*AMSR (J), GLI (J), ILAS-2 (J), POLDER (F),* SeaWinds	9
2003	ICESat	GLAS, GPS	
2003	SORCE	SIM, SOLSTICE, TIM, XPS	
2004	Aura	HIRDLS *(U.K./U.S.),* MLS, *OMI (N, Fin),* TES	
2004	PARASOL† *(France)*	POLDER	
2006	CALIPSO† *(France)*	CALIOP, *IIR (F),* WFC	8
2006	CloudSat	CPR *(U.S./C)*	8
Planned			
2008	Glory	APS, TIM	10
2008	NPP	ATMS, *CrIS (IPO), OMPS (IPO), VIIRS (IPO)*	10
2008	OSTM† *(France)*	*DORIS (F),* Microwave Radiometer, *Poseidon Altimeter (F),* TRSR	10
2008	OCO	Three grating spectrometers	8
2008	DSCOVR	EPIC (9-channel Earth Polychromatic Imaging Camera) NIST Advanced Radiometer (single-pixel, broadband)	10
2009	Aquarius† *(Argentina)*	LBR, LBS	8
2010	GPM CORE	*DPR (J),* GMI	3, 10

Table 2. Instrument Complement of the Coordinated Earth System Science Satellite Measurements of NASA and Its Partners.

Notes:

1. Meteor-3/TOMS ceased operations in 1994, ADEOS (Midori) ceased operations in 1997, and UARS and TOPEX/Poseidon ceased operations in 2005. EP/TOMS, although degraded, is still providing useful data, greatly exceeding its designed lifetime.
2. OrbView-2 is a 'data buy' from industry. It is not provided or operated by NASA.
3. TRMM and GPM are joint U.S./Japan missions.
4. AIRS, AMSU-A, HSB, AMSR-E, and MODIS data are available via direct broadcast (X band).
5. ASTER data are available via direct downlink.
6. The New Millennium Program (NMP) is charged to develop and flight-validate breakthrough technologies that will reduce the cost of high-priority science missions of the 21st century while enhancing their scientific capability.
7. SAC-C is an international cooperative mission between the Argentine Comision Nacional de Actividades Espaciales (CONAE) and the U.S. NASA, with contributions from Brazil, Denmark, France, and Italy.
8. The Earth System Science Pathfinder (ESSP) program is designed to explore Earth's dynamic systems and to achieve maximum science value while complementing existing or planned flight missions. The Principal Investigator for each ESSP mission is responsible for developing the flight mission hardware from selection to a launch-ready condition within 36 months and, along with the mission team, is responsible for accomplishing the science objective.
9. ADEOS II (Midori II) is a Japanese mission. It ceased operations prematurely in October 2003.
10. These missions are currently under study or are in the Formulation Phase. Current information is preliminary and will be made final at future Mission Confirmation Reviews.

Spacecraft marked with '†' are not provided or only partly provided by NASA.

Instruments in italics are not funded by NASA.

Key to countries/organizations providing the instruments:
Argentina (A), Brazil (B), Canada (C), Denmark (D), France (F), Finland (Fin), Germany (G), Italy (I), Japan (J), Netherlands (N), United Kingdom (U.K.), United States (U.S.), NOAA-DoD-NASA Integrated Program Office (IPO)

Table 2. Instrument Complement of the Coordinated Earth System Science Satellite Measurements of NASA and Its Partners *(cont.)*.

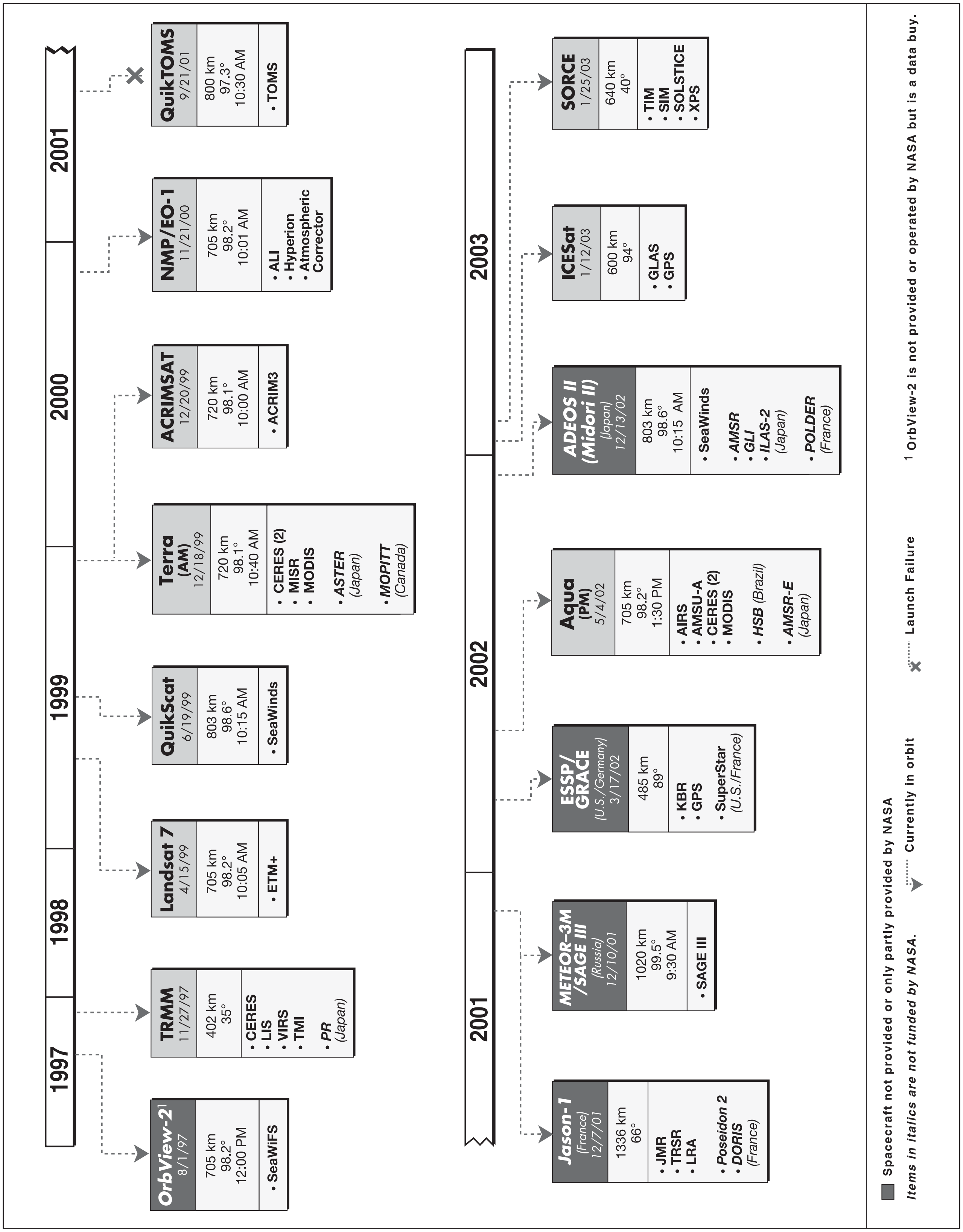


Figure 2a. Earth Science Mission Profile, 1997–2003, showing satellite name, launch date, altitude, inclination, equatorial crossing time, and instruments.

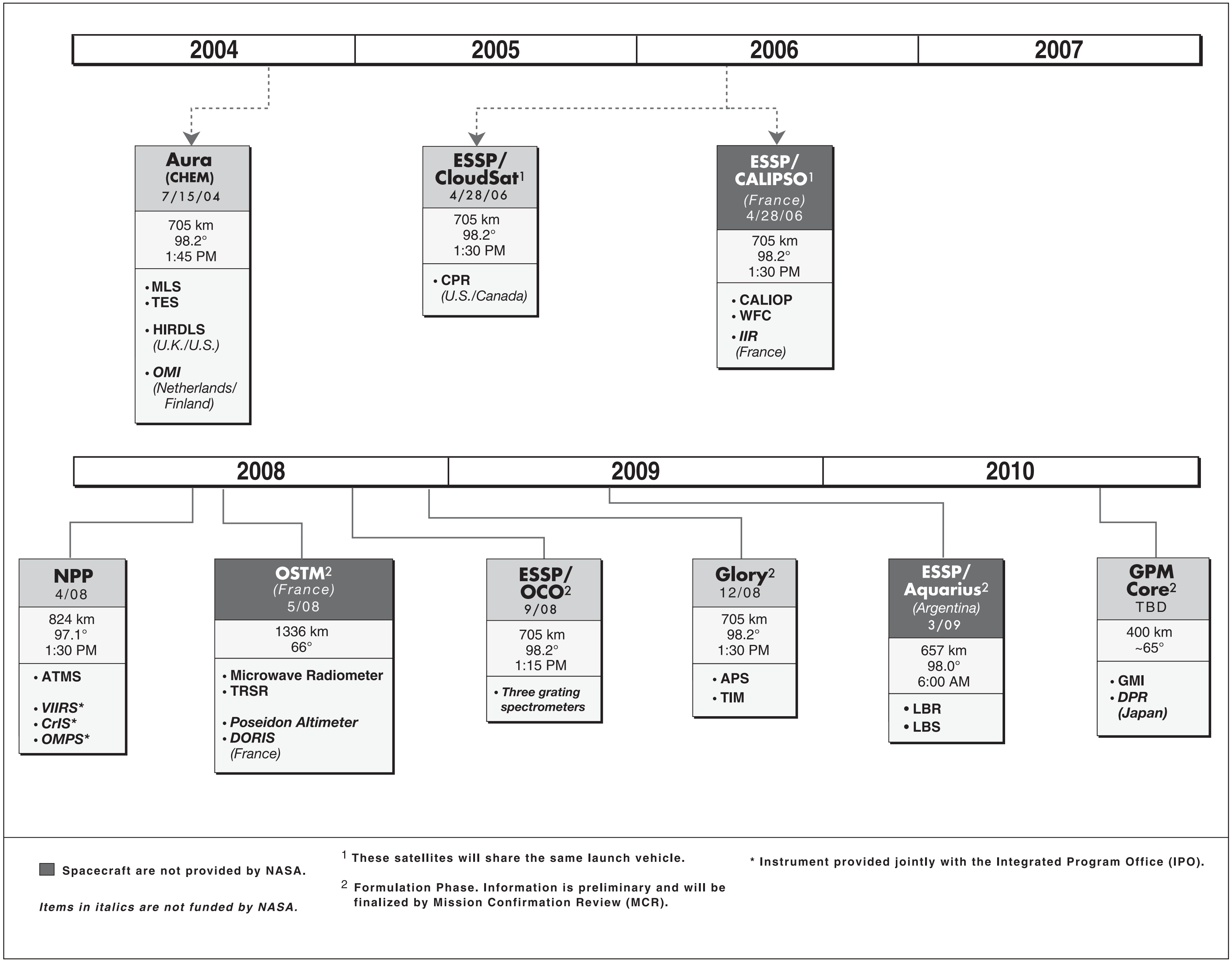


Figure 2b. Earth Science Mission Profile, 2004–2010, showing satellite name, launch date or anticipated launch month, altitude, inclination, equatorial crossing time, and instruments.

Instrument	Platform #	1997	1998	1999	2000	2001	2002	2003	2004	2005
ACRIM III	19									
AIRS	3									
ALI	5									
AMSR-E	3									
AMSU-A	3									
ASTER	1									
(CALIPSO)	18									
CERES	1, 3, 14			4	3	2	4	4	4	4
(CloudSat)	9									
ERBE	21									
ETM+	2									
GLAS	6									
(GRACE)	17									
HALOE	15									
HIRDLS	4									
HRDI	15									
HSB	3									
JMR	11									
LIS	14									
MISR	1									
MLS	4								2	2
MODIS	1, 3						2	2	2	2
MOPITT	1									
OMI	4									
PEM	15									
Poseidon-1	13									
Poseidon-2	11									
SAGE III	10									
SeaWiFS	12									
SeaWinds	7, 8							2		
SOLSTICE	15									
(SORCE)	16									
SUSIM	15									
TES	4									
TMR	13									
TOMS	20									
Average Data Rate *Mbps*		0.071	0.071	30.9	33.1	33.2	40.9	41.4	47.2	47.3
Instruments Operating in Flight		12	12	21	22	25	33	36	39	41

Table 3. Instrument Complement Satellite Platform Instrument Counts and Data Rates.

Platform # and Average Data Rates	Notes
1. Terra *17.848 Mbps* 2. Landsat 7 *12.963 Mbps* 3. Aqua *7.755 Mbps* 4. Aura *5.856 Mbps* 5. EO-1 *2.188 Mbps* 6. ICESat *0.450 Mbps* 7. QuikSCAT (SeaWinds) *0.040 Mbps* 8. ADEOS II/Midori II (SeaWinds) *0.040 Mbps* 9. CloudSat *0.025 Mbps* 10. Meteor-3M (SAGE III) *0.024 Mbps* 11. Jason *0.024 Mbps* 12. OrbView-2 (SeaWiFS) *0.023 Mbps* 13. TOPEX/Poseidon *0.020 Mbps* 14. TRMM (CERES & LIS) *0.016 Mbps* 15. UARS *0.011 Mbps* 16. SORCE *0.007 Mbps* 17. GRACE *0.005 Mbps* 18. CALIPSO *0.003 Mbps* 19. ACRIMSAT *0.001 Mbps* 20. EP/TOMS *0.0005 Mbps* 21. ERBS *0.0003 Mbps*	In the table on the left page, thirty-two instruments are entered in a column and the numbers beside them (Platform #) correspond to the numbers of the satellite platforms on which they fly, listed on this page in descending order of average data rates. Four of the entries in the Instrument column are actually satellite platform names (CALIPSO, CloudSat, GRACE, and SORCE), and these names are enclosed in parenthesis. Four platforms launched before 1997 (i.e., ERBS, 1984; UARS, 1991; TOPEX/Poseidon, 1992; and EP/TOMS, 1996) are beyond their designed lifetimes but are still providing useful data as of early 2006. (The two oldest missions have deteriorated considerably from their original states; e.g., the scanner on ERBS stopped working in 1990, and data are being acquired from only five of the original 10 instruments on UARS.) Numbers along the timeline bars indicate copies in orbit once the instruments have commenced routine operations. For example, there were three CERES instruments operating after the launch of Terra in 1999: one onboard TRMM and two onboard Terra. (See Table 2.) The 'Instruments Operating in Flight' row provides the maximum number of instruments operating at the same time during the year. The real-time data rate of the ALI instrument onboard EO-1 is 105 Mbps. However, only 4 snapshots are taken each day and their total readout time is only about 30 minutes (or 1/48 of a day). Hence, the data rate averaged over a day is given as 105/48 = 2.188 Mbps. All missions except ADEOS II (which ceased operations on 10/25/03) are shown as continuing beyond 2005, although some have already exceeded their design lifetime and may fail. However, a number of new missions, currently in the 'Formulation Phase', are being planned for the remainder of the decade and beyond. (See Table 2.)

Table 3. Instrument Complement Satellite Platform Instrument Counts and Data Rates *(cont.)*.

Validation Program

NASA manages a comprehensive Validation Program to verify geophysical measurements obtained by satellite sensors. In support of the program, the EOS Instrument Science Teams are responsible for algorithm validation and specification of the uncertainties in the high-level geophysical quantities derived from calibrated instrument measurements. Guidelines, policies, coordination, and the review process for EOS-wide validation activities are the responsibility of the Earth-Sun Exploration Division, with support and implementation by the Validation Scientist within the EOS Project Science Office. Pre-launch activities include development and verification of algorithms and characterization of uncertainties resulting from parameterizations and their algorithmic implementation. Post-launch activities include refinement of algorithms and uncertainty estimates based on near-direct comparisons with correlative measurements and selected controlled analyses or application implementations. Airborne measurements using specifically designed EOS instrument simulators and community airborne instruments also play an essential role in pre-launch and post-launch studies.

The Airborne Science Program complements the Validation Program by providing aircraft capable of both *in situ* and remote sensing to perform scientific experiments that demonstrate the feasibility of new sensors before producing a space-based system and to validate the measurements of new satellite-borne sensors. Examples of recent airborne campaigns are described briefly in Table 4.

Current information concerning the EOS Validation Program is available at: eos.nasa.gov/validation/.

References

Greenstone, R., and M. D. King, 1999: *EOS Science Plan: Executive Summary*. NASA GSFC, Greenbelt, MD, 64 pp.

Johnson, B. C., M. Litorja, and J. J. Butler, 2003: Preliminary results of aperture area comparison for exo-atmospheric solar irradiance. *Proc. Soc. Photo-optical Instr. Engineers (SPIE)*, 5151, 454–462.

King, M. D., and R. Greenstone, eds., 1999: *1999 EOS Reference Handbook.* NASA GSFC, Greenbelt, MD, 361 pp. [Available online at: eos.nasa.gov/ftp_docs/handbook99.pdf.]

King, M. D., R. Greenstone, and W. Bandeen, eds., 1999: *EOS Science Plan, The State of Earth Science in the EOS Program*. NASA GSFC, Greenbelt, MD, 397 pp. [Available online at: eos.nasa.gov/science_plan/index.php.]

NASA, 2003: *Earth Science Enterprise Strategy, October 2003*. NASA Headquarters, Washington, DC, 94 pp. [Available online at: science.hq.nasa.gov/strategy/index.html.]

NASA Earth System Science and Applications Advisory Committee (ESSAAC), 1994–Present: *Agenda and Minutes of Biannual Meetings.* [Available online at: science.hq.nasa.gov/strategy/essaac/index.html.]

NASA Earth Observing System: eospso. gsfc.nasa.gov

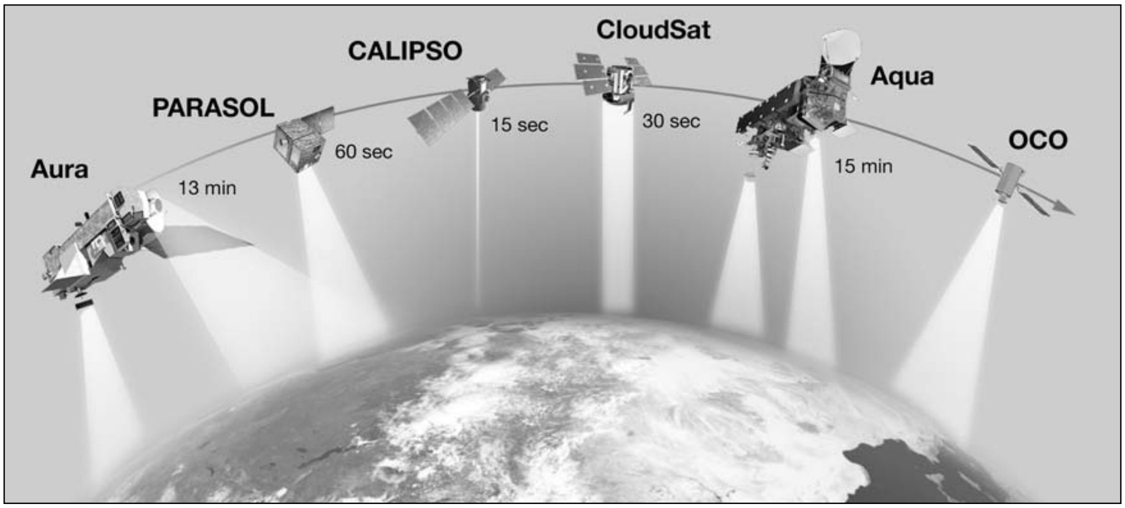


Figure 3. Satellites of the A-Train, showing the schematic alignment of six of the satellites, flying in essentially the same orbit with equatorial crossings at about 1:30 a.m. and 1:30 p.m., local time, that will constitute the afternoon constellation or 'A-Train'. The Glory satellite is expected to join the A-Train also, after its planned launch in 2008. Aqua, PARASOL, and Aura were all in orbit by the end of 2004.

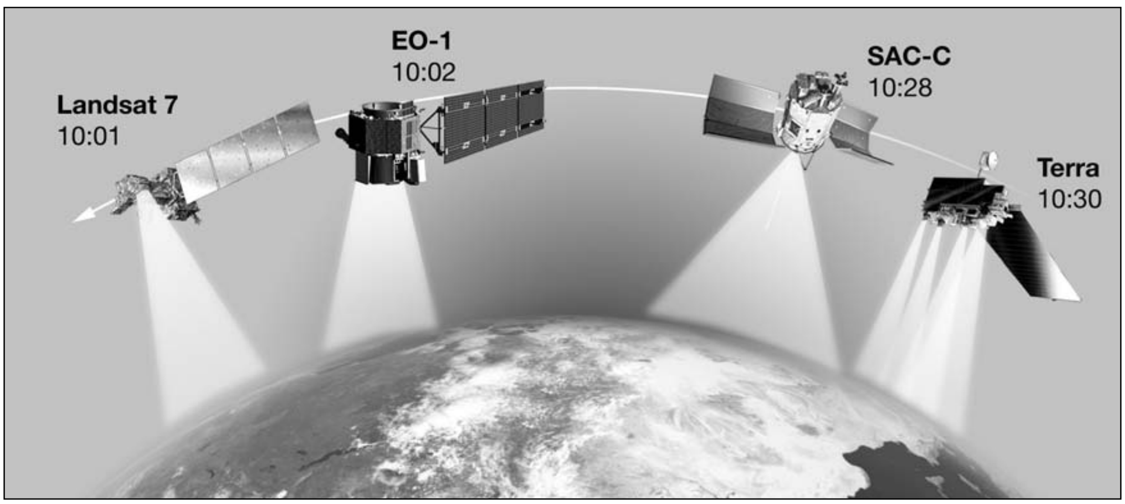


Figure 4. Satellites of the morning constellation, showing the schematic alignment of the four satellites, currently flying in essentially the same orbit with equatorial crossings at about 10:30 a.m. and 10:30 p.m., local time.

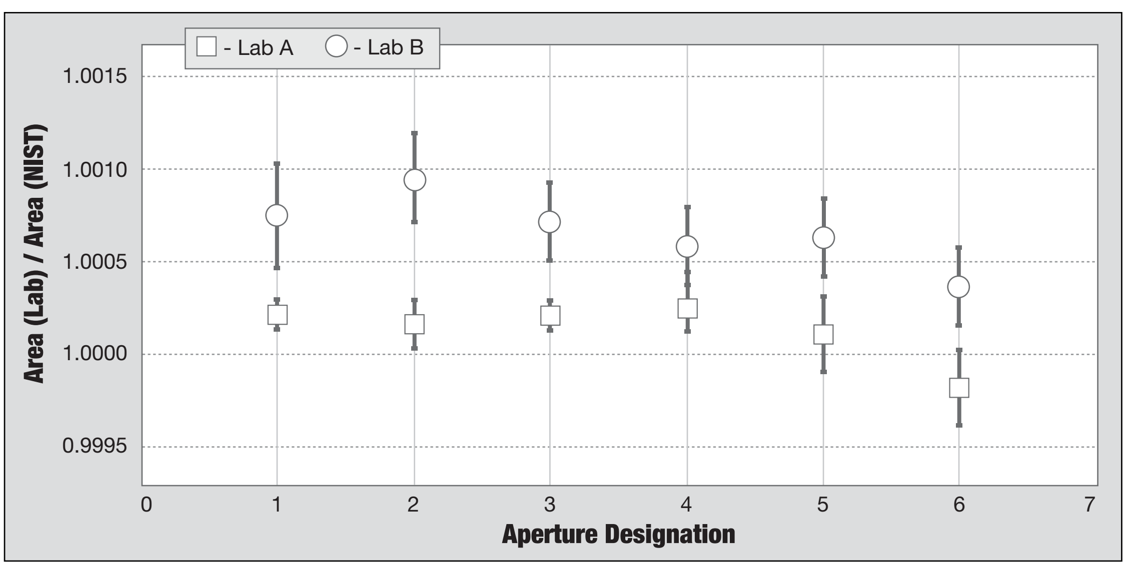


Figure 5. Results of a round-robin aperture-area comparison, showing preliminary calibration results on six aperture measurements made at two laboratories. Results are shown as the ratio of the laboratory area to the area measured by NIST. The vertical lines correspond to the combined expanded uncertainties.

1. **SAFARI 2000** (Southern African Regional Science Initiative - Dry Season Campaign)

Objective: Increase understanding of the Southern African ecological and climate system. Interdisciplinary science activity involved satellite overpasses and field measurement teams covering eight countries.

Lead Investigator: Michael D. King (NASA/GSFC)

Location: Polokwane (Pietersburg), South Africa

Time Period: August - September 2000

Aircraft: NASA ER-2, SAWS Aerocommander 690A (2 aircraft), U. Wash CV-580

Primary Airborne Sensors on the ER-2: MAS, MOPITT-A, AirMISR, SSFR, CPL, S-HIS, LAS, RC-10 Camera

2. **CLAMS** (Chesapeake Lighthouse and Aircraft Measurements for Satellites)

Objective: Perform closure experiment with the CERES Ocean Validation Experiment (COVE) sea platform. Validate Terra satellite-based retrievals of aerosol properties and vertical profiles of radiative flux, temperature, and water vapor.

Lead Investigator: William L. Smith Jr. (NASA/LaRC)

Location: Chesapeake Bay Lighthouse, VA

Time Period: July - August 2001

Aircraft: NASA ER-2, NASA OV-10, U. Wash CV-580, Proteus, Cessna 210, Learjet

Primary Airborne Sensors on the ER-2: AVIRIS, MAS, AirMISR, S-HIS

3. **SMEX02** (Soil Moisture Experiment 2002)

Objectives:
1) Validate the soil moisture algorithm developed for the Aqua AMSR-E over a well-understood target region.
2) Validate Aqua AMSR-E brightness temperature products over land using aircraft and ground-based microwave radiometry.
3) Explore new instrument technologies.

Lead Investigators: Tom Jackson (USDA) and Eni Njoku (NASA JPL)

Location: Ames, Iowa

Time Period: Late-June to mid-July 2002

Aircraft: NASA P-3B, NASA DC-8, NCAR C-130

Primary Airborne Sensors: PSR, ESTAR, AirSAR, PALS, GPS

4. **CRYSTAL-FACE** (Cirrus Regional Study of Tropical Anvils and Cirrus Layers - Florida Area Cirrus Experiment)

Objective: Investigate tropical cirrus cloud physical properties and formation processes. Understanding the production of upper tropospheric cirrus clouds is essential for the successful modeling of the Earth's climate.

Lead Investigator: Eric Jensen (NASA/ARC)

Location: Jacksonville, FL, South Florida

Time Period: July 2002

Aircraft: NASA ER-2 WB-57, Proteus, Twin Otter, UND Cessna Citation II, NRL P-3 (more than 50 instruments on six aircraft)

Primary Airborne Sensors on the ER-2: MAS, CPL, CRS, COSMIR

Table 4. Representative Airborne Field Campaigns.

5. **AMSR-E Rainfall Physical Validation**

Objective: Investigate the several assumptions in the retrieval of rainfall from the observations of AMSR-E on Aqua, by using an instrumented aircraft flying over precipitation while Aqua is passing overhead.

Lead Investigator: Thomas Wilheit (Texas A&M)

Location: Yokota Air Base (Wakasa Bay and surrounding water and land areas), Japan

Time Period: January - February 2003

Aircraft: NASA P-3B

Primary Airborne Sensors: PSR, PR-2, Cloud Radar, MIR, AMMR (21/37 GHz up-looking)

6. **AMSR-E Arctic Sea Ice Validation**

Objective: Validate the AMSR-E standard products of sea ice concentration, sea ice temperature, and snow depth on sea ice by making intercomparisons among *in situ* (near Barrow and at a Beaufort Sea ice camp), aircraft, and satellite measurements, including those from Aqua (AMSR-E, MODIS), ICESat, RADARSAT, and Landsat 7.

Lead Investigator: Donald Cavalieri (NASA/GSFC)

Location: Fairbanks, AK, Barrow, AK, Bering Sea, Beaufort Sea, Chukchi Sea

Time Period: March 2003

Aircraft: NASA P-3B

Primary Airborne Sensors: PSR-A, PSR-CX, TAMMS, ATM

7. **Hawaii-2003** – THORpex, ASAP, NPOESS Validation Techniques, MODIS/AIRS Validation, GLAS Validation

Objectives for each of the five parts of this cooperative campaign:

- THORpex - Investigate impact of Gulf of Alaska weather on 0-10 day forecasts
- ASAP - Investigate the relationship between weather products and aircraft safety (part of the NASA Advanced Satellite Aviation - weather Products Program)
- NPOESS - Validate AIRS/AMSU-A/HSB observations (using the NPOESS Airborne Sounder Testbed, NAST)
- MODIS/AIRS - Validate Terra/Aqua MODIS & Aqua AIRS observations
- GLAS - Validate ICESat/GLAS observations

(Note: THORpex is an international research program to search for better ways to observe parts of the atmosphere crucial to forecasting extreme weather more than a week ahead.)

Lead Investigators (respectively): M. Shapiro (NOAA/IPO), J. Murray (NASA/LaRC), William L. Smith, Sr. (NASA/LaRC), S. Ackerman and C. Moeller (U. Wisc.), J. Spinhirne (NASA/GSFC)

Location: Hawaii, Pacific Ocean, Gulf of Alaska

Time Period: February - March 2003

Aircraft: NASA ER-2, NOAA Gulfstream IV (MOBY buoy)

Primary Airborne Sensors: MAS, NAST-I/M, CPL, S-HIS, LaRC O3 Probe, RC-10 Camera, Dropsondes

8. **CLPX 03** (Cold Land Processes Experiment 2003)

Objective: Develop and test methods for the remote sensing of cold land processes in three study areas in Colorado.

Lead Investigator: Donald Cline (NOAA National Operational Hydrologic Remote Sensing Center)

Location: Colorado

Time Period: Late February and late March 2003

Aircraft: NASA P-3B, NASA DC-8 (late March only), Twin Otter (NOAA Aero Commander, U. Wyoming King Air)

Primary Airborne Sensors: PSR, AirSAR, POLESCAT, WindRad, AVIRIS

Table 4. Representative Airborne Field Campaigns *(cont.).*

9. **SMEX 03** (Soil Moisture Experiment 2003)

Objectives:
1) Validate Aqua/AMSR-E soil moisture products for a range of land cover types.
2) Develop and verify soil moisture retrieval algorithms.
3) Demonstrate new soil moisture retrieval concepts.

Lead Investigators: Tom Jackson (USDA) and Eni Njoku (NASA JPL)

Location: Oklahoma, Georgia, Alabama

Time Period: June–July 2003

Aircraft: NASA P-3B, NASA DC-8

Primary Airborne Sensors: PSR, AirSAR, 2DSTAR, GPS

10. **AMSR-E Antarctic Sea Ice (AASI) validation campaign**

Objectives:
1) Assess the accuracy of sea ice parameters derived from Aqua AMSR-E data using the AMSR algorithm
2) Establish the optimum values of the reference AMSR brightness temperatures for sea ice and open water
3) Quantify the variability of the emissivity and temperature of sea ice, and improve algorithm performance at the marginal ice zone.

Lead Investigator: Josefino Comiso (NASA/GSFC)

Location: Punta Arenas, Chile, Weddell Sea, Bellingshausen Sea

Time Period: October 2004 (Note: This mission was originally scheduled to be flown in 2003 but was aborted because of aircraft engine problems and was rescheduled for 2004.)

Aircraft: NASA P-3B (NSF Ship)

Primary Airborne Sensors: PSR-A, PSR-CX, GPS, THOR system, TAMMS, ESTAR, ATM D2P

Below: Locations of Representative Airborne Field Campaigns. The circled numbers correspond to the numbered campaigns in this table.

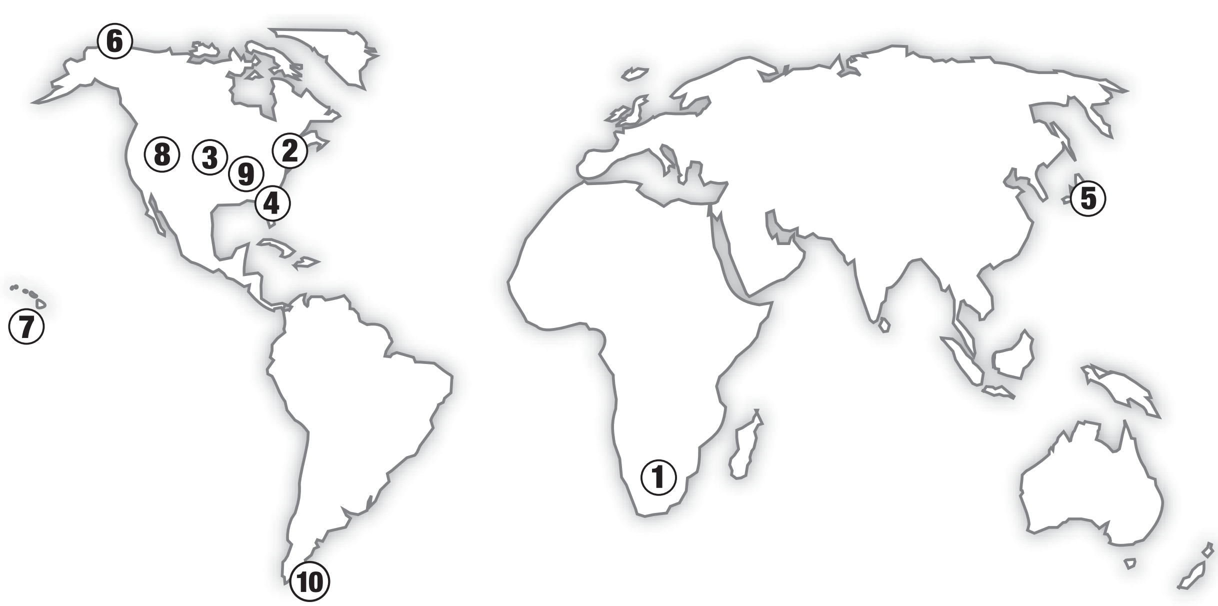


Table 4. Representative Airborne Field Campaigns *(cont.).*

Earth Observing System Data and Information System

The success of NASA's Earth Science Mission is contingent on providing easy access to Earth science data for a wide community of users. To meet this commitment, the Earth Observing System Data and Information System (EOSDIS) has been operating since August 1994 at eight Distributed Active Archive Centers (DAACs) around the United States and has also been interoperating with six foreign sites.

At present, EOSDIS is managing unprecedented amounts of data from NASA's past and current Earth science research satellites and field-measurement programs and also providing data archiving, distribution, and information-management services. Since its inception in 1990, EOSDIS has used an adaptive approach. Over the years, several steps have been taken to distribute the responsibility for provision of basic services and thereby increase the flexibility of EOSDIS. Most of the science data products are generated on Science Investigator-led Processing Systems (SIPSs) under the direct control of the instrument teams, while a few products are generated using the science data-processing systems in the DAACs. In either case, the respective instrument teams provide the algorithms and scientific quality assurance. The subsystems/components deployed in EOSDIS consist of both centrally developed large-scale elements (the EOSDIS Core System [ECS], and the EOS Data and Operations Systems [EDOS]) and smaller-scale specialized capabilities developed by DAACs and other organizations.

The components of EOSDIS interface with each other and with external systems to support the data flows needed for capturing, processing, archiving, and distributing the data. Examples of data are: command data uplinked for operating the spacecraft and instruments; housekeeping and engineering telemetry for monitoring the health and safety of the spacecraft and instruments, science data from satellites, ancillary data and other instrument data needed for generation of science data products from a given instrument, quality-assessment data from the instrument teams to be associated with the data products to be archived, and requests for data from users employing one of several search-and-access mechanisms. Data are transmitted to users via electronic networks.

EOSDIS elements cooperate with other U.S. and international organizations in all aspects of development, operations, data processing, and distribution. EOSDIS and its DAACs provide access to science data products from EOS spacecraft, other Earth science spacecraft, and *in situ* data.

Services Provided by EOSDIS

EOSDIS is a comprehensive data and information system designed to perform a wide variety of functions in support of a heterogeneous national and international user community. To this end, NASA's comprehensive Earth Science data systems provide a spectrum of services, primarily intended for research scientists working in NASA's Science Focus Areas and specific research disciplines but open also to the general public and the international science community. The entities providing these services may vary over time as a result of an adaptive approach, including both for the infrastructure provided by EOSDIS and Mission data systems and for competed community elements. Services provided by EOSDIS are complemented by other data system activities selected through NASA Research Opportunities in Space and Earth Science (ROSES) announcements such as the Research, Education, and Applications Solutions Network (REASoN) and Advancing Collaborative Connections for Earth System Science (ACCESS) projects. In addition, NASA funds mission-specific data systems outside the EOS Program and measurement data systems such as the Ocean Color Data Processing System and the Precipitation Processing System. The primary services provided by EOSDIS are summarized below. Spacecraft Command and Control, Data Capture and Level 0 Processing, and Networks/Communications are all handled by Mission Systems of EOSDIS and are managed by the Earth Science Mission Operations (ESMO) Project at the Goddard Space Flight Center (GSFC). The remaining services are handled by Science Systems of EOSDIS and are managed by the Earth Science Data and Information System (ESDIS) Project at GSFC.

Spacecraft Command and Control—The EOSDIS control center performs command and control, and planning and scheduling for the spacecraft and onboard instruments. These functions include processing data-acquisition requests, coordination of multi-instrument observations, ensuring that the commands generated are valid and within resource constraints, monitoring and maintenance of the health and safety of spacecraft and instruments, analyzing spacecraft data, and maintaining history of spacecraft and instrument operations. The control center provides the instrument teams a web-based interface to monitor instrument and spacecraft activities. EOSDIS also provides appropriate interfaces to ensure command and control of International Partners' instruments onboard

EOS spacecraft and EOS instruments onboard non-EOS spacecraft.

Data Capture and Level 0 Processing—EOSDIS captures 'raw' data from all EOS spacecraft and processes them to remove telemetry errors, eliminate communication artifacts, and create Level 0 Standard Data Products that represent raw science data as measured by the instruments (see Key EOSDIS Science Data Product Terminology later in this chapter). Some EOS instruments are designated as prototype operational environmental-monitoring instruments. The data from those instruments are made available to the National Oceanic and Atmospheric Administration (NOAA) within three hours of data acquisition, to support operational weather forecasts. For EOS instruments flying on non-EOS spacecraft, the EOS-instrument data are captured by the respective ground systems and received by EOSDIS for higher-level data processing, archiving, and distribution.

Product Generation—EOSDIS supports data product generation from EOS instrument observations. EOS investigators develop algorithms and software for EOS data products as part of their scientific studies. NASA and the EOS Project Science Office (PSO) review specifications for standard products to ensure that they are complete and consistent and that they satisfy the goals of the EOS mission. Prior to the launch of each instrument, a group of Earth scientists participated in a peer review of the physical, chemical, and biological bases for these products and the soundness of the approach used to generate them. NASA sets the priorities for the processing and reprocessing needed to generate standard products, in consultation with the appropriate Earth science communities. The priorities are assigned based on scientific requirements, technical considerations, and cost.

Data Archive, Management, and Distribution—The data holdings archived, managed and distributed by EOSDIS include data products derived from the satellite missions and scientific campaigns, plus other related data and information. EOSDIS stores all the standard products computed from the EOS instruments during the mission life and distributes requested data to users electronically (via networks). In addition, EOSDIS stores and distributes data from non-EOS sources that are needed for EOS standard-product generation. Also, product-generation algorithms, software, documentation, calibration data, engineering specifications, and other ancillary data are stored and provided to users upon request. Sufficient information is stored about the system-configuration history to be able to regenerate products in case of accidental or catastrophic loss. Access to the current suite of EOSDIS data holdings may be obtained via the DAACs. Also allied with the EOSDIS DAACs is the Global Hydrology Resource Center (GHRC).

Information Management—EOSDIS provides convenient mechanisms for electronically locating and accessing products of interest. The look and feel of the system is intuitive and uniform across the multiple nodes from which EOSDIS can be accessed. EOSDIS facilitates collaborative science by providing extensible sets of tools and capabilities such that investigators may provide access to special products (or research products) from their own computing facilities. EOSDIS has a currently operational EOS Data Gateway (EDG) that provides 'one-stop-shopping' access to the data holdings at all the EOSDIS DAACs and participating data centers from other U.S. and international agencies. Several EDGs around the world permit users to access Earth science data archives, browse data holdings, select data products, and place data orders. These gateways provide access to information about EOS data products plus other Earth science data. The EOS products include a suite of metadata attributes and values that provide enhanced search capabilities. In addition, specialized services at each of the EOSDIS DAACs can be accessed via their individual interfaces. A new paradigm in data search and retrieval is being introduced with the EOS Clearing House (ECHO). ECHO is a clearinghouse of spatial and temporal metadata enabling the science community to exchange data and information. ECHO technology can provide value-added services and work as an order broker (middleware) between client and data partners while supporting efficient discovery and access to Earth science data. The EDG will be replaced by a new client, Warehouse Inventory Search Tool (WIST), which retains the essential features of EDG. ECHO also facilitates development of focused, discipline-specific clients for searching and accessing data.

Complementary to the above information management services is the Global Change Master Directory (GCMD), which provides descriptions of Earth science data sets and services relevant to global change research. The GCMD holds more than 16,200 data set descriptions and 1,400 Earth science service descriptions, which consist of information on how to obtain the data or service and often include direct access to the data or service. Over 4,000 EOS and Earth Science Information Partner (ESIP) data sets and services are searchable from the GCMD. The GCMD encompasses all areas of Earth science, including atmosphere and climatology, biosphere and environmental science, hydrosphere and oceans, snow and ice, geoscience, paleoclimatology, land surface, Sun-Earth connections, and human dimensions of climate change. The Earth science services cover areas such as data and visualization and GIS products, data handling, models and decision support tools, and environmental and hazard advisories.

User Support—The DAACs have User Support Services to assist users in data acquisition, search, access, and usage. While most of the interaction by users with EOSDIS is through human-computer interfaces, occasional consultation will be needed with the User Support Services staff for assistance with specialized questions regarding the data or the system. The DAACs provide support services to users from the public and private sectors, including research scientists, educators, students, users in public agencies responsible for operational applications such as weather forecasting and environmental monitoring, policy makers, and the public in general.

EOSDIS Components

EOSDIS uses a distributed, open-system architecture. This permits allocation of EOSDIS elements to various locations to take best advantage of different institutional capabilities and science expertise. EOSDIS includes several major components—EOS Mission Operations System (EMOS), EDOS, EOS Networks, DAACs, Science Data Processing Segment (SDPS), and the SIPSs. EMOS, EDOS, and EOS Networks constitute the Mission System of EOSDIS, managed by GSFC's ESMO Project. The remaining components form the Science System of EOSDIS managed by GSFC's ESDIS Project.

An overview of the EOSDIS components and their interrelationships is shown in Figure 6. The following paragraphs provide details of each of the major components. Each component is essential to the successful operation of EOSDIS.

EOS Mission Operations System (EMOS)—EMOS consists of the EOS Operations Center (EOC) located at GSFC and a number of Instrument Support Terminals (ISTs) at the instrument teams' facilities. The EOC controls the Terra, Aqua, and Aura spacecraft, provides mission planning and scheduling, and monitors health and safety of the spacecraft and instruments. It provides tools to coordinate observations from multiple instruments and develop conflict-free schedules, validates commands to assure safety, accommodates unplanned schedule changes, develops and provides mission timelines, and develops and implements contingency plans. It interacts with the various elements of the ground systems and space network, as necessary, to send commands to EOS spacecraft and to receive health and safety data from the spacecraft. It interacts with the International Partners' instrument-control centers for exchange of planning and command and control information. The EOC is implemented using a combination of commercial mission-control systems and custom software.

EOS Data and Operations System (EDOS)—EDOS captures high-rate science and engineering data from the EOS spacecraft and instruments, processes telemetry to generate Level 0 products, and maintains a backup archive of Level 0 Science Data Products for the Terra, Aqua, and Aura missions. It removes telemetry artifacts, creates sets of non-overlapping raw data as sensed by the individual instruments over specific time intervals, and sends these data to the appropriate DAAC. In the case of a data loss at any of the DAACs, the data can be recovered from the backup archive within EDOS. In the case of loss of a part of the backup Level 0 data within EDOS, the corresponding data can be recovered from the appropriate DAAC. Level 0 data are provided by EDOS to a DAAC as Production Data Sets (PDSs) or Expedited Data Sets (EDSs) for processing by the DAAC or an associated SIPS.

The EOS Real Time Processing System (ERPS) provides the interface between control centers and ground stations for Terra, Aqua, and Aura. ERPS provides ground services for data processing, distribution, and storage for low-rate return-link data, and processing, delivery, and logging for forward-link data conforming to the Consultative Committee for Space Data Systems (CCSDS) Recommendations for Space/Ground Data Communications. ERPS provides the capability to use Transmission Control Protocol/Internet Protocol (TCP/IP) for the transfer of real-time data between the Goddard Space Flight Center (GSFC)-based EOC and the remote ground terminals.

EOS Networks—Effective access to EOSDIS depends on network connectivity between users and data sources. The DAACs and Mission Systems are connected through the EOS Mission Support network (EMSn), which uses the NASA Integrated Services Network (NISN)-provided Premium IP (PIP) network to assure security, timeliness, and predictable response. This network moves Level 0 Science Data products from EDOS to DAACs and supports inter-DAAC data flows for generation of interdependent EOS products. The EMSn also provides secure, reliable communications for low-rate forward-and-return-link operations.

The EOS Science Support network (ESSn) provides connectivity between DAACs and users' systems. Several organizations provide ESSn services including: 1) NISN Standard IP (SIP) service for access to other NASA centers, the commodity Internet, and some National and International High Performance Research and Education Networks, and 2) the Mid-Atlantic Xroads (MAX) GigaPoP and the University Corporation for Advanced Internetworking Development's (UCAID) Abilene Network for access to most universities and most International High Performance Research and Education Networks.

Distributed Active Archive Centers (DAACs)—Eight DAACs, representing a wide range of Earth science disciplines, carry out the responsibilities for processing, archiving, and distributing EOS and related data, and for providing a full range of user support (Table 5). These institutions are custodians of Earth science data from EOS and several non-EOS/heritage missions and ensure that data will be easily accessible to users. Acting in concert, DAACs provide reliable, robust services to users whose needs may cross traditional discipline boundaries, while continuing to support the particular needs of their respective discipline communities. The DAACs are currently serving a broad and growing user community with increasing use of both EOS and non-EOS data. Each DAAC has a working group of users to provide advice on priorities for scientific data, levels of service, and needed capabilities. The DAACs have actively participated in the design and implementation of EOSDIS.

Science Data Processing Segment (SDPS)—SDPS supports data archiving, data distribution, and information management. SDPS hardware and software, developed as a part of ECS, reside and operate at the DAACs. SDPS provides for ingest and storage (temporary or permanent, depending on data type) of data sets needed from other data centers for supporting the generation of standard data products. It supports the extraction of appropriate subsets of standard data products to assist in scientific quality control by respective investigators; and it also provides software toolkits to assist instrument teams in their development of product-generation software at their Science Computing Facilities (SCFs).

Science Investigator-led Processing Systems (SIPSs)—With the exception of the standard products derived from the ASTER instrument on Terra, MISR on Terra, and AIRS/AMSU/HSB on Aqua, all EOS standard products are produced at SIPSs. These facilities are under the direct control of the instrument Principal Investigators/Team Leaders (PIs/TLs) or their designees. SIPSs are generally, but not always, collocated with the PIs/TLs Scientific Computing Facilities. For those Standard Data Products generated by a SIPS, a DAAC captures the Level 0 and ancillary data products and stores them for retrieval by SIPSs. Products produced at SIPSs, using investigator-provided systems and software, are sent to appropriate DAACs for archiving and distribution. One exception to this is the Ocean Color Data Processing System, which processes, archives, and distributes the MODIS ocean products.

EOSDIS Evolution

Due to the extended operational lifetimes of the missions it supports and the science community's desire to continually increase access to the large data holdings of EOSDIS, the ESDIS Project has undertaken an evolution process to accommodate changes in technology and user requirements and to address improvements in data access. Some of the key science goals in the original design of the system included the need to support data search and access, dynamic product life cycle and extensible product sets, interactive investigations, information-rich logical data collections, integration of independently developed investigators' tools and software, user-to-user collaboration, distributed administration and control, and site autonomy. The evolution process seeks to continue to meet these goals while making improvements across the board.

To reach its joint goals for science support and evolution, EOSDIS has been developed as a logically distributed system with the DAACs and SIPSs. It has sufficient modularity and standard interfaces to enable migration and/or replacement of components. It is built with a selection of subsystems and services tailored to particular data types and other specific needs. It permits autonomy for service providers, while providing for coordination among them.

Evolution of EOSDIS is discussed below in the context of the overall evolution of Earth science data systems supported by NASA. The first subsection below presents the evolution of the EOSDIS components and services, and the second presents comments on the other data systems activities supported by NASA that are complementary to EOSDIS.

Evolution of EOSDIS Components and Services—Over the course of its development, many EOSDIS design changes have been implemented in response to changes in user needs and/or advances in data- and information-systems technology. The integration of EDG and SIPSs with ECS, to provide information-management and data-processing services, are two examples. Another is the implementation of facilities called data pools, which are large caches of on-line storage that hold the latest and most popular data collections. The data pools provide direct access to these data collections with a growing set of available services including subsetting and standard interfaces.

While EOSDIS is managing a large amount of data and successfully serving a broad user community, its design and development originated more than 10 years ago. Many advances have occurred in information technology during the intervening years. Although there have been on-going technology infusion, incremental improvements in processing and performance, and new functionality added in user access, distribution, and archive management over the years, the underlying design has remained essentially the same. During this time frame, data volumes have grown dramatically and the science community has gained considerable experience in processing and analyzing the data. More recently, through examination of current operations and a series of lessons learned, there has been a desire to re-examine current operations in search of system improvements in a variety of areas. To this end, in 2004 NASA convened two groups: an EOSDIS Elements Evolution Study Team to provide an external viewpoint and offer guidance, and an EOSDIS Elements Evolution Technical Team to develop an approach and implementation plan that would begin to fulfill the objectives set forth in a 2015 Vision developed in February 2005 by the Study Team. The objectives set by NASA's Science Mission Directorate for the EOSDIS evolution were:

- Increase end-to-end data system efficiency and operability
- Increase data usability by the science research, application and modeling communities
- Provide services and tools needed to enable ready use of NASA's Earth science data in next-decadal models, research results, and decision support system benchmarking
- Improve support for end users

The vision formulated by the Study team and the plans formulated by the Technical Team address the above objectives. More detail on these can be found at: eosdis-evolution.gsfc.nasa.gov/.

Evolution of NASA Earth Science Data-Management Systems—While the evolution of EOSDIS is driven in part by changes in user requirements and technology, it is also in response to guidance from NASA and its advisory panels to move toward a more distributed and heterogeneous collection of data- and information-systems providers to satisfy the data-management needs of the Agency. To that end, NASA has sponsored several initiatives complementary to EOSDIS. The first was the award of the Earth Science Information Partners (ESIPs) in 1999 followed by the initial REASoN awards in 2004 and ACCESS awards in 2006. These projects comprise teams from government, academic, and commercial institutions that are funded to produce value-added products and services consistent with the goals and objectives of NASA's Earth Science programs.

In order to foster community involvement in the evolution of NASA's Earth Science Data Systems, four Earth Science Data System Working Groups have been established. These are: the Standards Process Group, Metrics Planning and Reporting Working Group, Software Reuse Working Group, and Technology Infusion Working Group. These working groups are open to all interested parties and have membership from the ESDIS Project, DAACs, SIPS, and REASoN and ACCESS Projects. They conduct focused studies on data management issues in their respective areas and make recommendations to NASA's Science Mission Directorate for incorporation into its planning.

Key EOSDIS Science Data Product Terminology

Standard Data Products (SDPs)—Data products are to be considered SDPs if they are:

- generated as part of a research investigation using EOS data,
- of wide research utility,
- routinely generated, and
- produced for spatially and/or temporally extensive sets of data.

Level Definitions for EOS SDPs—The various levels of data referred to in this document are identical to those defined by the EOSDIS Data Panel, and are consistent with the Committee on Data Management, Archiving, and Computing (CODMAC) definitions. For some instruments, there will be no Level 1B product that is distinct from the Level 1A product. In these cases, the reference to Level 1B data can be assumed to refer to Level 1A data. Brief definitions follow:

- **Level 0**
  Reconstructed, unprocessed instrument/payload data at full resolution; any and all communications artifacts, e.g., synchronization frames, communications headers, duplicate data removed. In most cases these data are provided by EDOS to a DAAC as Production Data Sets for processing to the SDPs in the DAAC or by the SIPSs to produce the higher-level products.

- **Level 1A**
  Reconstructed, unprocessed instrument data at full resolution, time-referenced, and annotated with ancillary information, including radiometric and geometric calibration coefficients and georeferencing parameters, e.g., platform ephemeris, computed and appended but not applied to the Level 0 data.

- **Level 1B**
  Level 1A data that have been processed to sensor units (not all instruments have Level 1B data products).

- **Level 2**
  Derived geophysical variables at the same resolution and location as the Level 1 source data.

- **Level 3**
  Variables mapped on uniform space-time grids, usually with some completeness and consistency.

- **Level 4**
  Model output or results from analyses of lower level data, e.g., variables derived from multiple measurements.

All EOS instruments must have Level 1 SDPs; most have products at Level 2 and Level 3; and some have Level 4 SDPs. Some EOS Interdisciplinary Science Investigations have also generated Level 4 SDPs. Specifications for the set of SDPs to be generated are reviewed by EOSPSO and NASA Headquarters to ensure completeness and consistency in providing a comprehensive science data output for EOS. Standard data products are produced at DAACs or SIPSs.

References

Asrar, G., and H. K. Ramapriyan, 1995: Data and Information System for Mission to Planet Earth. *Remote Sens. Rev*. **13**, 1–25.

National Research Council, 1994: Panel to Review EOSDIS Plans: Final Report, National Academy Press, Washington, D.C.

National Research Council, 1995: A Review of the U.S. Global Change Research Program and NASA's Mission to Planet Earth/Earth Observing System, National Academy Press, Washington, D.C.

Price, R. D., M. D. King, J. T. Dalton, K. S. Pedelty, P. E. Ardanuy, and M. K. Hobish, 1994: Earth science data for all: EOS and the EOS Data and Information System. *Photogrammetric Eng. Remote Sens*. **60**, 277–285.

EOSDIS: eos.nasa.gov/eosdis

EOSDIS Evolution: eosdis-evolution.gsfc.nasa.gov

ESDSWG: seeds.gsfc.nasa.gov

Table 5. Data Centers, Disciplines, and Contact Information.

Data Center	Discipline	User Support Office Contact Information
Alaska Satellite Facility *ASF Distributed Active Archive Center (DAAC)*	Synthetic Aperture Radar (SAR), Sea Ice, Polar Processes, and Geophysics	*Phone:* 907-474-6166 *Fax:* 907-474-2665 *Email:* asf@eos.nasa.gov *URL:* www.asf.alaska.edu
GSFC Earth Sciences Data and Information Services Center *GES DAAC*	Atmospheric Composition, Atmospheric Dynamics, Global Precipitation, Ocean Biology, Ocean Dynamics, and Solar Irradiance	*Phone:* 301-614-5224, 1-877-422-1222 *Fax:* 301-614-5268 *Email:* gsfc@eos.nasa.gov *URL:* daac.gsfc.nasa.gov
Global Hydrology Resource Center *GHRC*	Hydrologic Cycle, Severe Weather Interactions, Lightning, and Convection	*Phone:* 256-961-7932 *Fax:* 256-961-7859 *Email:* ghrc@eos.nasa.gov, user-services@ghrc.nsstc.nasa.gov *URL:* ghrc.msfc.nasa.gov
Langley Research Center *LaRC DAAC*	Radiation Budget, Clouds, Aerosols, and Tropospheric Chemistry	*Phone:* 757-864-8656 *Fax:* 757-864-8807 *Email:* larc@eos.nasa.gov *URL:* eosweb.larc.nasa.gov
Land Processes *LP DAAC*	Land Processes	*Phone:* 605-594-6116, 1-866-573-3222 *Fax:* 605-594-6963 *Email:* LPDAAC@eos.nasa.gov *URL:* LPDAAC.usgs.gov
National Snow and Ice Data Center *NSIDC DAAC*	Snow and Ice, Cryosphere and Climate	*Phone:* 303-492-6199 *Fax:* 303-492-2468 *Email:* nsidc@eos.nasa.gov, nsidc@nsidc.org *URL:* nsidc.org
Oak Ridge National Laboratory *ORNL DAAC*	Biogeochemical Dynamics, Ecological Data for Studying Environmental Processes	*Phone:* 865-241-3952 *Fax:* 865-574-4665 *Email:* ornldaac@eos.nasa.gov *URL:* www.daac.ornl.gov
Physical Oceanography *PO.DAAC*	Oceanic Processes and Air-Sea Interactions	*Phone:* 626-744-5508 *Fax:* 626-744-5506 *Email:* podaac@eos.nasa.gov, podaac@podaac.jpl.nasa.gov *URL:* podaac.jpl.nasa.gov
Socioeconomic Data and Applications Center *SEDAC*	Population, Sustainability, Geospatial Data, and Multilateral Environmental Agreements, Natural Hazards, Poverty	*Phone:* 845-365-8920 *Fax:* 845-365-8922 *Email:* sedac@eos.nasa.gov *URL:* sedac.ciesin.columbia.edu

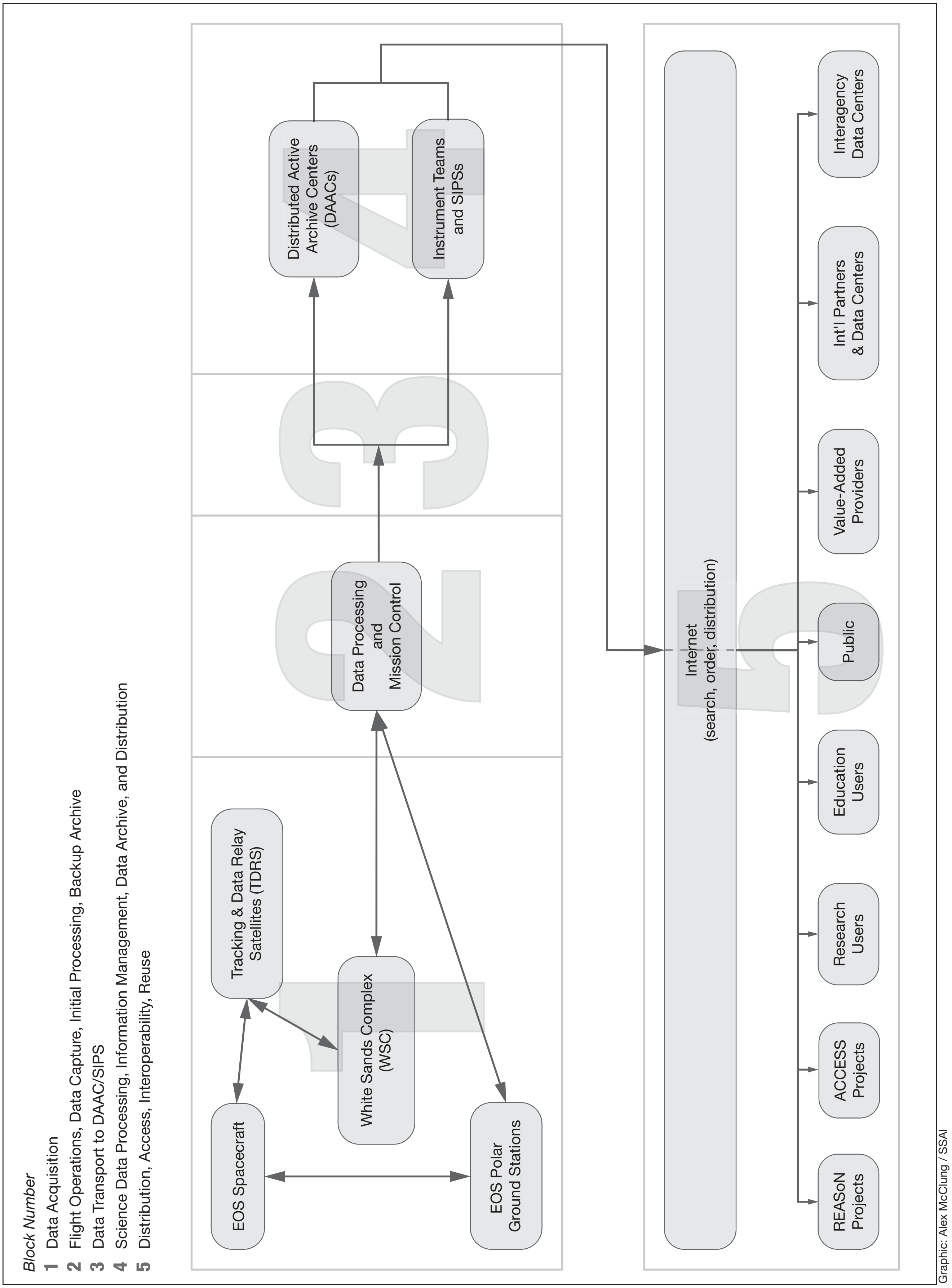


Figure 6. EOSDIS Context.

Data and Information Policy

NASA Earth Science Statement on Data Management

NASA's Earth Science program was established to use the advanced technology of NASA to understand and protect our home planet by using our view from space to study the Earth system and improve prediction of Earth system change. To meet this challenge, NASA promotes the full and open sharing of all data with the research and applications communities, private industry, academia, and the general public. The greater the availability of the data, the more quickly and effectively the user communities can utilize the information to address basic Earth science questions and provide the basis for developing innovative practical applications to benefit the general public.

A common set of carefully crafted data exchange and access principles was created by the Japanese, European and U.S. International Earth Observing System (IEOS) partners during the 1990s and the early years of the 21st century. From these principles, NASA has adopted the following data policy (in this context the term 'data' includes observation data, metadata, products, information, algorithms, including scientific source code, documentation, models, images, and research results):

- NASA will plan and follow data acquisition policies that ensure the collection of long-term data sets needed to satisfy the research requirements of NASA's Earth science program.

- NASA commits to the full and open sharing of Earth science data obtained from NASA Earth observing satellites, sub-orbital platforms and field campaigns with all users as soon as such data become available.

- There will be no period of exclusive access to NASA Earth science data. Following a post-launch checkout period, all data will be made available to the user community. Any variation in access will result solely from user capability, equipment, and connectivity.

- NASA will make available all NASA-generated standard products along with the source code for algorithm software, coefficients, and ancillary data used to generate these products.

- All NASA Earth science missions, projects, and grants and cooperative agreements shall include data management plans to facilitate the implementation of these data principles.

- NASA will enforce a principle of non-discriminatory data access so that all users will be treated equally. For data products supplied from an international partner or another agency, NASA will restrict access only to the extent required by the appropriate Memorandum of Understanding (MOU).

- In keeping with the Office of Management and Budget (OMB) Circular A-130, NASA will charge for distribution of data no more than the cost of dissemination. In cases where such dissemination cost would unduly inhibit use, the distribution charge will generally be below that cost.

- Through MOUs and agreements with appropriate interagency partners, NASA will ensure that all data required for Earth system science research are archived. Data archives will include easily accessible information about the data holdings, including quality assessments, supporting relevant information, and guidance for locating and obtaining data.

- NASA will engage in ongoing partnerships with other Federal agencies to increase the effectiveness and reduce the cost of the NASA Earth science program. This interagency cooperation shall include: sharing of data from satellites and other sources, mutual validation and calibration data, and consolidation of duplicative capabilities and functions.

- NASA will, in compliance with applicable Federal law and policy, negotiate and implement arrangements with its international partners, with an emphasis on meeting the data acquisition, distribution, and archival needs of the U.S.

- NASA will collect a variety of metrics intended to measure or assess the efficacy of its data systems and services, and assess user satisfaction. Consistent with applicable laws, NASA will make those data available for review.

The data collected by NASA represent a significant public investment in research. NASA holds these data in a public trust to promote comprehensive, long-term Earth science research. Consequently, NASA developed policy consistent with existing international polices to maximize access to data and to keep user costs as low as possible. These policies apply to all data archived, maintained, distributed or produced by NASA data systems.

References

The National Aeronautics and Space Act of 1958, as amended, 42 U.S.C. §2451, *et seq*.

The Land Remote Sensing Policy Act of 1992, 15 U.S.C. §5601, *et seq*.

The Paperwork Reduction Act, 44 U.S.C. §3501, *et seq*.

The Freedom of Information Act, as amended, 5 U.S.C. §552 (1994), amended by P. L. 104-231.

OMB Circular A-130 (February 8, 1996)

National Space Policy (NSTC-8, September 19, 1996).

Presidential Directive (NSPD-7), Space-Based Global Change Observation (May 28, 1992).

Statements on Data Management for Global Change Research (Office of Science and Technology Policy, July 1991).

Mission to Planet Earth Commercial Strategy (March 1997).

IEOS Data Exchange Principles.

Applied Sciences Program

NASA's objective for its Applied Sciences Program is to expand and accelerate the realization of economic and societal benefits from Earth science, information, and technology. This objective is accomplished by using a systems approach to facilitate the assimilation of Earth observations and predictions into the decision-support tools used by partner organizations to provide essential services to society, services that include management of forest fires, coastal zones, agriculture, weather prediction, hazard mitigation, and aviation safety. In this way, NASA's long-term research programs yield near-term practical benefits to society. Thus, the Applied Sciences Program enables NASA's Earth science efforts to be citizen-centered, results-oriented, and market-driven.

The Applied Sciences Program focuses on forging partnerships with other Federal agencies and views this as the most efficient means to extend the benefits of Earth science information and technology to the Nation and beyond. Federal agencies such as the Department of Agriculture (USDA), Federal Emergency Management Agency (FEMA), Environmental Protection Agency (EPA), and others have charters to provide essential services to meet national needs. These agencies have existing webs of connections to end users in state, local, tribal, national, and foreign organizations and governments to whom improvements in those services can be extended, so that by working together NASA does not have to forge its own connections. Furthermore, Federal agencies have the information infrastructure and decision-support systems capable of taking advantage of NASA's Earth science data and information.

As depicted in Figure 7, NASA remote-sensing systems and Earth system models are inputs generating observation and prediction outputs that in turn are used as inputs to our partners' decision-support systems. The outcomes are improved decision-support tools enabling positive impacts on national policy and management decisions in a range of activities from coastal evaluations of hurricane impacts to positioning of fire-fighting resources in national forests. The target impacts are improvements to the quality and effectiveness of policy and management decision making by enabling decision makers to benefit from decreasing uncertainties associated with complex and dynamic Earth system processes. The outputs shown in Figure 7 indicate the bridge that the Applied Sciences Program and its partners build between Earth science results and decision-support tools. This area is the focus of the Applied Sciences Program.

The Applied Sciences Program employs the following strategic principles in pursuit of its objectives:

- Enable the practical use of Earth science information and technology in ways that are systematic, scalable, and sustainable, thus magnifying the benefit of Earth system science to the nation.

- Partner with other federal agencies having decision-support systems that can, or can be enhanced to, assimilate observations from remote-sensing systems and predictions from Earth system models. NASA works with its partner agencies to benchmark (measure) the improvement from use of new observations and predictions.

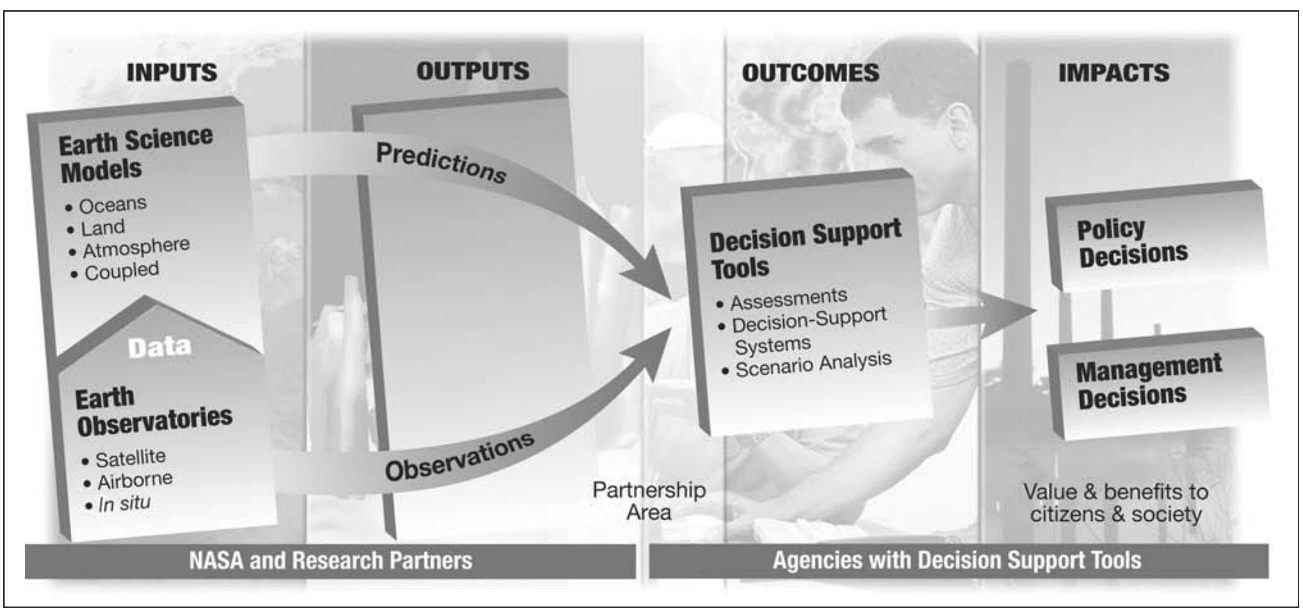


Figure 7. Applied Sciences Program Approach to Integrated Systems Solutions.

- Employ NASA's systems engineering expertise to enable the effective assimilation of NASA Earth science results, information, and technology in our partners' decision-support systems.

- Engage the capacity of universities, industries, and others through competitive solicitation for products, tools, and techniques employing remote-sensing observations and Earth system models in sponsored applications projects.

- Engage in national efforts to coordinate geospatial information principles and practices (interoperability, standards, metadata, etc.), such as the Geospatial One-eStop (www.geodata.gov) and the Federal Enterprise Architecture, to assure the utility of the vast quantity of data collected by several agencies engaged in *in situ*, airborne, or satellite remote sensing.

- Employ the national Commercial Remote Sensing Policy as a guide to the acquisition and use of commercially available remote-sensing data for research and applications.

The Applied Sciences Program's purpose, approach, and intended outcomes are consistent with the recognition by the U.S. government's executive and legislative branches of the value of using Earth science information and technology to improve the many decision-support systems employed by the public and private sectors to deliver essential services. The Climate Change Science and Technology Programs have both embraced the paradigm proceeding from observing systems to models to decision-support systems, underpinned by research, as a structured means of delivering science for society. This basic approach also serves as one basis for the next phase of international collaboration on Earth observation. The beginning of this new phase was marked by the international Earth Observation Summit held in July 2003, which inaugurated planning for a global Earth observation system aimed at providing environmental information necessary for improving the quality of life and stewardship of planet Earth.

The 12 Applied Science Program Elements

NASA has 12 program elements under the Applied Sciences Program. It forms partnerships with other federal agencies that can significantly benefit from NASA's observations and research results.

The program elements are detailed and summarized in the following paragraphs and in Table 6. In addition, each program element interfaces with one or more of the six science focus areas (described in the Earth Science Program section) as depicted in the matrix shown in Figure 8.

Agricultural Efficiency

An increased understanding of weather and climate can help to improve agricultural competitiveness, especially through the improved accuracy and lead-time of event prediction.

Economies all over the world are impacted by interannual climate anomalies, and the consequences can be severe. Many of these anomalies can be linked to global phenomena such as El Niño or La Niña. Scientists from NASA and partner agencies seek to better understand the complexities of the seasonal variability of climate, which can contribute to providing accurate and timely information to farmers and organizations responsible for food and water management. The results of NASA research and development in Earth science and technology can be integrated into local and regional decision-support systems addressing issues related to weather and climate predictions in agriculture management. Improvements in the accuracy of these decision structures lead to improved crop-production assessments and increased agricultural productivity and reliability.

Air Quality

In recent decades, considerable focus has been placed on improving the quality of the air we breathe. Global measurements reveal that pollution is not exclusively a regional issue. NASA researchers and others have confirmed that pollutants are lofted high into the atmosphere and transported hundreds, even thousands of miles—crossing oceans and national boundaries. Research conducted at NASA and measurements taken by various NASA missions support improved models of pollution initiation and transport. The measurements serve as input into a modeling system maintained by EPA that helps to improve the accuracy and lead-time of pollution forecasts and allows for robust emissions-control planning.

Aviation

To compete effectively in the global economy of the 21st century, the U.S. needs a healthy and vibrant aviation industry. Since weather is a contributing factor in approximately 30% of all aviation accidents, aviation meteorologists need accurate upper-air data and timely, accurate data concerning volcanic eruptions and plume dispersion in order to route air traffic around dangerous natural phenomena. Improved aviation forecasts are critically dependent on accurate upper-air observations (often from radiosonde or satellite soundings). Studies have shown that the impact of weather and other natural phenomena upon aviation could be substantially mitigated if existing satellite information were utilized more effectively. To address these challenges, NASA is utilizing satellite remote-sensing systems to provide the frequent, densely distributed observations needed by the NASA Advanced Supercomputing system. NASA and its partners are working diligently to make sure that information available from instruments on current and future satellite missions is infused into operational forecasting techniques in a more timely fashion.

Carbon Management

Carbon is the basis for the food and fiber that sustain life on Earth and is also a primary energy source around the globe. Carbon dioxide (CO_2) is a major greenhouse gas whose concentration increased over 25% in the 20th century, with undetermined climate and societal consequences. Natural ecosystems on land and in the oceans serve as carbon sinks, absorbing over half of the CO_2 that human activities insert into the atmosphere each year. Research indicates that changes in land-management practices could enhance the effectiveness of these terrestrial and oceanic carbon sinks in offsetting potential harmful effects of increased atmospheric CO_2 concentrations. NASA is uniquely poised to contribute information relevant to this research; its space-based missions are making significant contributions to carbon management studies by enabling global and regional measurements and/or analysis of: the concentrations of CO_2 in the troposphere; the impact of regional land, atmosphere, and ocean interactions on CO_2 concentrations; the impact of soil-carbon concentration and farming practices on soil-carbon-sequestration activities and effectiveness; and the amount of vegetation biomass as a measure of carbon sources and sinks on land. The results of these efforts can be integrated directly into local, regional, and global decision-making tools and should lead to improved ability to assess how carbon sources and sinks may be altering the global CO_2 concentration and the development of a carbon-trading regime.

Coastal Management

Earth's coastal regions provide the habitat for vital ecosystems incorporating many marine and terrestrial species, as well as providing crucial resources for humans, birds, and other life forms. Our shorelines are under siege from a number of natural and human-affected phenomena. Global warming threatens to raise the level of the oceans and inundate our coastal lands. Harmful algae blooms and hypoxia, caused by excess nutrient concentrations from runoff, starve our waters of dissolved oxygen and wreak havoc on marine ecosystems and coastal economies. Over 7000 square miles of the Gulf of Mexico are hypoxic—the largest swath in the Western Hemisphere. Since 1978, NASA has been collecting information relevant to coastal-management studies. NASA works with its partners to provide these quality science observations and predictions as input into coastal-management models. The anticipated result is improved ability to forecast these menacing threats to our coasts and improved ability to plan for them and mitigate their harmful impacts on society.

Disaster Management

Community preparedness for disaster management involves assessments of vulnerability, risk, and response to short-lived phenomena in Earth's atmosphere, land, and oceans. Particular episodic events of concern are thunderstorms, tornadoes, hurricanes, tsunamis, flooding, volcanic ash, forest fires, earthquakes, harmful ocean blooms, and human-made disasters such as petroleum releases in rivers and oceans. Correct forecasts of natural phenomena are vitally important to allow for proper evacuation and damage-mitigation strategies without unwarranted expenditures and loss of public confidence that occurs when incorrect warnings are issued. NASA Earth science data are being incorporated into improved decision-support systems to meet the requirements of planners, early warning systems, and first responders, and to contribute to impact assessments, risk communication, mitigation, and implementation of relief efforts.

Ecological Forecasting

Ecological forecasting uses Earth observation data and models to predict the impacts of environmental changes on the ecosystems upon which society depends for its very existence. It links the physical world of climate and geology to the living world of biology and ecology. The goal is reliable forecasts of changes in living systems with uncertainties and estimates of error explicitly stated. There will no doubt be limits to what can be forecasted but discovering these limits and their causes will enhance overall understanding of the ecosystems and enhance efforts to manage and preserve them. NASA is currently involved in several international and domestic partnerships under the theme of ecological forecasting. The decision-support systems engendered will be vital to efforts to build economies while at the same time sustaining the natural ecosystems that provide all-important free services such as: clean air, fresh water, fertile soils, waste removal, and biodiversity. The desire is to create a win-win situation where various critical ecosystems are maintained even as the economies dependent on a particular ecosystem expand and as populations living within the confines of that ecosystem increase.

Energy Management

The commercial and residential demand for energy is affected by natural and human influences. Growth in urban areas changes land surfaces from green areas to heat islands, creating complex microclimates. Population concentrations increase localized gas emissions of pollutants that impact local air quality and contribute to the overall greenhouse effect. These human activities occur against a backdrop of natural variability such as seasonal weather patterns, climatic extremes (floods, droughts, severe cold), and interannual climate variations that account for changes in energy consumption. The challenge facing decision makers is to predict accurately the variability of both natural and human influences on climate in order to plan more effectively for energy use and conservation. Development of decision-support systems for energy forecasting will impact government and industrial organizations at all levels. A major component of NASA is dedicated to understanding Earth's energy and hydrological cycles from remote sensing and modeling.

Homeland Security

Since the terrorist attacks of September 11, 2001, efforts to protect our nation have redoubled. The nation's air and water resources could be particularly vulnerable to future attacks. Contamination and disruption in these basic environmental quantities, be it by terrorist attack or other human-induced or natural disasters, would have profound consequences for society. Thus, it is essential that proactive monitoring and forecasting efforts be implemented to minimize the vulnerability of these vital resources. NASA's measurements, observations, and modeling can provide data and information to Homeland Security networks to support risk, vulnerability, and mitigation assessments. Earth science data and information can support decision making to ensure the adequacy of preparing for, preventing, responding to, and recovering from terrorist threats or attacks. NASA's current and future space-based missions will offer a wealth of information relevant to monitoring the quality of the water we drink and the air we breathe. The combination of adequate soil-moisture and precipitation data and global-scale air-quality measurements, all combined with improved understanding of climatic phenomena such as ocean-circulation anomalies, will greatly enhance weather and climate forecast skill, thus enabling us to better cope with future homeland security threats.

Invasive Species

Non-indigenous invasive species pose among the most formidable threats of the 21st century. An 'invasive species' is defined as a non-native species whose introduction causes, or is likely to cause, harm to the economy, environment, or human health. Non-indigenous invasive species include: 1) mosquitoes responsible for diseases such as malaria and West Nile Virus that affect public health; 2) agricultural pathogens; and 3) plant and animal species that compete with native species and/or have significant negative economic impact. The issue has developed diverse interested stakeholders, including land-management agencies, states, the agricultural industry, conservation organizations, and private landowner groups. NASA and the U.S. Geological Survey (USGS) are combining their resources and shared expertise to create a National Invasive Species Forecasting System for the management and control of invasive species. The end product will be a dynamic and flexible system to generate electronic and paper maps of 'hot spots' for potential exotic species invasions. These maps will be used by private and public national, state, and local management agencies for remediation, management, and control. NASA currently provides measurements that map key ecosystem attributes needed to predict invasive-species distributions and contribute to improvements in weather and climate predictions and ecological forecasting. NASA also provides the computational capabilities and expertise in large-scale, coupled, Earth system modeling needed to ensure the successful transfer of the data and technology into operational decision-support systems. These contributions assure operational, robust, and early detection and monitoring of outbreaks of invasive species to protect natural and managed ecosystems.

Public Health

Many chronic and infectious diseases are related to environmental conditions. Recent outbreaks of West Nile Virus and other vector-borne diseases have illustrated the importance of having accurate and timely information to predict and respond to epidemics. Organisms such as ticks and mosquitoes (called vectors) transport these diseases; and variabilities in rainfall and temperature have a major influence on the distribution and quantity of these organisms. NASA aims to help determine how weather, climate, and other key environmental factors correlate with the occurrence of chronic and infectious diseases. Once verified, validated, and benchmarked, these relationships can be assimilated into surveillance systems such as the Environmental Public Health Tracking Network to track and predict disease. NASA's satellites offer a wealth of information for input into the decision-support systems used for public health. The result of incorporating all of this information into decision support systems will be improved surveillance systems and more accurate and precise disease predictions allowing for increased lead-time on forecasts

Water Management

Viewed from above, our home planet is wonderfully multicolored, although with such an abundance of water on its surface that it is sometimes referred to as a 'blue marble'. Still, only a small amount of this water is fresh and suitable for consumption by plants, animals, and humans. Potable water availability, quality, and conservation issues impact every region of the country. Monitoring the quality of both surface and ground water, and identifying the location and magnitude of existing and potential pollution sources and impacts are essential to ensuring an adequate uncontaminated supply of this vital natural resource. Surface water includes both (a) flowing water in streams and rivers and (b) impounded water in natural lakes, polar ice caps, and human-made reservoirs. Ground water includes the large amounts of water stored beneath Earth's surface in aquifers. Increased demand threatens to deplete these reservoirs. A number of NASA missions contribute to our understanding of these and other key water-management concerns. These missions are providing data for studying water movement across the Earth's surface and are expected to allow for improved assessments of water storage both on and beneath the Earth's surface. Future missions will contribute more information leading to even better understanding of these issues. Incorporating this information in decision-support systems will lead to improved capability to predict water availability, protect water quality, and plan for water conservation.

	Agricultural Efficiency	Air Quality	Aviation	Carbon Management	Coastal Management	Disaster Management	Ecological Forecasting	Energy Management	Homeland Security	Invasive Species	Public Health	Water Management
Atmospheric Composition	Secondary	Primary	Secondary	Secondary					Secondary		Primary	
Carbon Cycle & Ecosystems	Primary			Primary	Secondary		Primary	Secondary		Primary	Primary	
Climate Variability & Change	Secondary	Secondary		Secondary	Primary	Secondary	Secondary	Primary		Secondary	Primary	Secondary
Earth Surface & Interior			Primary		Secondary	Primary			Primary			Secondary
Water & Energy Cycles	Primary			Secondary	Primary	Secondary	Secondary	Primary		Secondary		Primary
Weather	Primary	Secondary	Primary		Secondary	Primary		Primary				Secondary

Primary Linkages / Secondary Linkages

Figure 8. Earth Science Research and Applied Sciences Matrix.

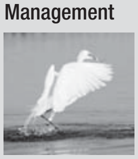
National Application	Partner Agencies	NASA Contributions	Partner Agencies' Decision Support Tools	Decadal Outcomes of Agencies' Use of NASA Data and Information
Agricultural Efficiency 	USDA, EPA	Seasonal temperatures and precipitation data, extended weather forecasts, and soil moisture data via Aqua, Terra, Landsat, suborbital missions, and, eventually GPM, NPP, and Aquarius.	• Crop Assessment Data Retrieval and Evaluation (CADRE).	• Improved crop production assessments • Increased agricultural productivity and reliability.
Air Quality 	EPA, NOAA, USDA, FAA	Measurements of aerosols, ozone, emissions, and modeling of aerosol and chemical atmospheric transport via Terra, Aura, suborbital missions, and, eventually, NPP and Glory.	• Community Multiscale Air Quality modeling system (CMAQ) • AIRNow and Air Quality Index.	• Multiple-day air quality forecasts and robust emissions control planning.
Aviation 	DOT/FAA	Monitoring of volcanic aerosols via Terra, Aqua, Aura, suborbital missions, and, eventually, NPP-Bridge, GPM; improved weather nowcasting; improved cockpit capabilities via: • Aviation Weather Information Network (AWIN) • Synthetic Vision System.	National Airspace System (NAS): • Controller/pilot decision aids • Runway incursion prevention.	• Enhanced National Airspace System, AWIN, and Synthetic Vision System that aim to reduce the aviation fatal accident rate by a factor of 10 by 2002 • Improved operational efficiency in a 2:1 ratio.
Carbon Management 	USDA, EPA, DOE, USGS, USAID	Measurements of carbonaceous gases and aerosols, terrestrial biomass and marine productivity via Terra, Aqua, Aura, suborbital missions, and, eventually, NPP and OCO.	• CQUEST tools developed to implement Section 1605(B) of the Energy Policy Act of 1992: voluntary sequestration of greenhouse gases.	• Operational decision support system with improved assessment of carbon sources and sinks for a carbon trading regime.
Coastal Management 	NOAA, EPA	Measurements and modeling of ocean temperatures, winds, color and salinity associated with harmful algae blooms via Terra, Aqua, SeaWinds, Landsat, Jason, and, eventually, NPP.	• Harmful Algae Bloom Mapping System/Bulletin (HABMap/Bulletin).	• Improved capability of decision support systems to forecast HAB initiation, transport, toxic severity, landfall, and demise.
Disaster Management 	FEMA, USGS, NOAA, USDA	Observations of topographic change and crustal strain and motion, extended weather forecasts via Aqua, SeaWinds, SRTM, Landsat, suborbital missions, and, eventually, GPM.	• HAZUS Risk Prediction • Center for Integration of National Disaster Information (CINDI).	• Enhanced risk assessment, warning and response for hurricanes, tornados, flooding, earthquakes, and landslides.

Table 6. Applied Science Program Elements showing Partner Agencies, NASA Contributions, Partner Agencies' Decision Support Tools, and Projected Decadal Outcomes of each program element.

National Application	Partner Agencies	NASA Contributions	Partner Agencies' Decision Support Tools	Decadal Outcomes of Agencies' Use of NASA Data and Information
Ecological Forecasting 	USGS, USDA USAID	Observation of land cover change, vegetation structure, and biomass, and use in ecosystem models via Landsat, suborbital missions, and, eventually, NPP.	• Models of habitat change • Impacts of El Niño and other oceanic oscillations on fisheries • Regional visualization and monitoring system for the Mesoamerican Biological Corridor.	• Enhancing ecosystem sustainability as economics and populations shift and grow.
Energy Management 	DOE, EPA	Extended weather forecasts, seasonal climate prediction, and distribution of incoming solar radiation via Terra, Aqua, SORCE, and, eventually, CloudSat, NPP, and GPM.	• RET Screen • Natural Resources Canada (NRCan).	• Energy Management sources and their integration into the power grid through use of RET Screen • Location of Energy Management Facilities • Biomass crop selection and maintenance strategies.
Homeland Security 	DHS, NIMA, USDA, USGS, NOAA, DoD	Observation and modeling of atmospheric chemical transport and precipitation via Terra, Aqua, Aura, suborbital missions, and, eventually, NPP and GPM.	• Department of Homeland Security (DHS) Situation Control.	• Improved capabilities of homeland security officials to prepare, warn, and respond to homeland security threats, especially air and water exposure.
Invasive Species 	USGS, USDA	Observations and modeling of land cover change, biomass and climate influencing species proliferation in areas where they have been newly introduced, via Terra, Aqua, Landsat, and, eventually, NPP.	• Invasive Species Forecasting System (ISFS).	• Operational, robust, and early detection and monitoring of plant invasions to protect natural and managed ecosystems.
Public Health 	CDC, DoD, NIH, EPA, USGS, NOAA	Observations and modeling of weather, climate and other environmental factors influencing disease vectors and air quality via Aura, Aqua, Terra, Jason, and, eventually, NPP and GPM.	• Environmental Public Health Tracking Network (EPHTN) • Arbovirus Surveillance Network (ArboNet) • Malaria Modeling and Surveillance (MMS).	• Arbovirus Surveillance Network (ArboNet) • Integrated environmental factors into EPHTN • Improved accuracy and precision of disease predictions with a corresponding increase in warning time.
Water Management 	USBoR, EPA, USDA, USGS	Improved models of water transport, storage and quality using observations of snow cover, soil moisture and topography via Aqua, Terra, GRACE, Landsat, suborbital missions, and, eventually, NPP and GPM.	• RiverWare • Better Assessment Science Integrating Point and Nonpoint Sources (BASINS) • Agricultural Water Resources and Decision Support (AWARDS).	• Improved water quality and quantity assessments • Forecasts of precipitation and daily crop water use towards reduction of unnecessary irrigation • Seasonal predictions for optimum vegetation selection and improved water use efficiency.

Table 6. Applied Science Program Elements showing Partner Agencies, NASA Contributions, Partner Agencies' Decision Support Tools, and Projected Decadal Outcomes of each program element *(cont.)*.

Education Program

Introduction

An essential element of inspiring the next generation of explorers is educating them to give them the skills they need to be pioneers of the 21st century. Through its education programs, NASA is well positioned to help motivate students toward careers in science, technology, engineering, and mathematics (STEM), provide educators with the tools they need to improve STEM instruction, and increase scientific literacy among the general public. They offer a diverse array of programs, activities, and resources based on NASA's unique missions and results.

Inspire the Next Generation of Earth Explorers (available at: science.hq.nasa.gov/education/) presents NASA's plan for Earth science education through 2008 and explains how Earth science education aligns with the framework set forth in the Agency's first Education Enterprise Strategy, *Learning in a Whole New Light* (available at: education.nasa.gov/about/strategy).

NASA's Earth science educational activities provide unique inquiry-based Earth system science content to engage students in new technologies and prepare them for participation in the 21st century global society. The Earth system science concept, in addition to changing the way research is conducted, is changing the way Earth science is taught at elementary through post-graduate levels and the way it is presented to the public by the media and informal learning communities.

Goals and Objectives

NASA views the concept of Earth explorers broadly. The elementary-school student questioning if El Niño occurs in oceans other than the Pacific, the researcher investigating connections between Arctic ozone depletion and global climate change, the consumer comparing hydrocarbon versus hydrogen-powered cars, the citizen scientist interested in how changing climate and/or changing land cover/land use affects animal migration patterns, the business person projecting future needs for harvest, transport, and storage of crops, and many others in various roles are all Earth explorers. All share a vital interest in Earth system processes and their impacts for life on Earth.

The following education program goals and associated objectives are aligned with Agency goals and objectives for education as outlined in the Education Enterprise Strategy:

Goal 1: To inspire and motivate students to pursue STEM careers by providing stimulating and challenging content using the results of Earth system science and Earth science applications.

Objectives

- Draw on the compelling nature of Earth system science to support teacher professional development and promote student achievement in STEM.
- Ensure the continued training of a highly qualified and diverse workforce to support Earth system science research and Earth science applications.
- Inspire and support underrepresented and/or underserved communities through each sponsored education program.
- Increase student, teacher, and public access to Earth system science education resources via electronic information infrastructures.

Goal 2: To increase public scientific literacy of Earth system science and climate change by engaging the public in shaping and sharing the experience of exploration and discovery.

Objectives

- Provide engaging Earth system science content and human-resource support to informal learning institutions for the benefit of all learners.
- Cultivate citizens' abilities to get the data, resources, and information they need to satisfy their own curiosity on how the Earth system works and/or to take actions to meet individual or societal needs.

NASA Education Program Operating Principles

NASA established Agency-wide Education Program Operating Principles to ensure alignment of all NASA education programs with the *2003 NASA Strategic Plan*, to ensure adherence to NASA value-transformation principles, and to promote excellence. The six operating principles are outlined in Table 7.

The *2003 NASA Strategic Plan* describes a new paradigm for exploration and discovery where: 1) all parts of NASA contribute to a common set of Agency objectives; 2) education programs utilize human space-flight activities to enhance learning opportunities; 3) education programs utilize technology to improve student learning; 4) education is built into all programs from their inception; and 5) all programs operate together as one NASA.

Approach

The approach chosen for inspiring the next generation of Earth explorers has two critical and complementary components. The first is the use of digital-information infrastructures as a principal mechanism for the systematic delivery of educational resources. The second is the formation of a network of partners to facilitate the integration of resources into existing education programs and activities. Figure 9 outlines the process by which these components contribute to the delivery of education activities for socioeconomic benefit.

To be fully utilized by the education community, science data sets and other resources must be easily accessible in easy-to-use formats. Efforts are ongoing to develop and apply hardware and software for research and education in a systematic way. Meanwhile, NASA works together with other federal agencies, educational administrations, academic institutions, professional societies, international organizations, and other industries to maximize the impact of education activities. These partnerships facilitate widespread dissemination and effective use of NASA's educational resources, promote alignment of the education program with national, state, and local STEM priorities, and support the development of a highly qualified Earth system science workforce. NASA and its partners are especially focused on increasing participation and retention of women, minorities, and persons with disabilities in the Earth sciences.

The content for NASA Earth Science educational resources and programs is based on the six major science focus areas for research regarding the Earth system: climate variability and change; atmospheric composition; carbon cycle, ecosystems and biogeochemistry; water and energy cycles; weather; and Earth surface and interior. NASA, along with other federal agencies and affiliated laboratories, institutions of higher education, and non-governmental organizations (NGOs), engages in research supporting these six focus areas.

Programs, Activities, and Resources

NASA targets both formal and informal education audiences, providing wide-ranging opportunities for learners of all ages to investigate Earth system processes using the Agency's unique resources. Educational content is based on the six science focus areas listed above. A complete listing of programs, activities, and resources is available online at: earth.nasa.gov/education/catalog. They are also featured in the "For Kids," "For Students," and "For Educators" sections of the NASA portal (www.nasa.gov), NASA's electronic point of entry for the nation and the world.

Sponsorship of educational projects is through competitive sourcing with specific focus and through efforts that are embedded in Directorate research programs and flight missions. The Earth-Sun System Education Program, in the Science Mission Directorate at NASA Headquarters, is primarily responsible for program planning, selection, reporting, and integration. The education offices at the NASA Centers also participate in the planning and implementation of Agency-level education programs and lead the development of education programs that are unique to their Centers. Center education offices ensure compliance of these activities within the priorities established by the Education Program Office.

Criteria	Description
Customer Focused	Programs or products have been designed to respond to a need identified by the education community, a customer or customer group.
Content	Programs or products make direct use of NASA content, people, or facilities to involve educators, students, and/or the public in NASA science, technology, engineering, and mathematics.
Pipeline	Workforce-related programs or products make a demonstrable contribution to attracting diverse students to NASA careers and lifelong learning in science, technology, engineering, and mathematics.
Diversity	Programs or projects reach identified targeted groups.
Evaluation	Programs or products implement an evaluation plan to document outcomes and demonstrate progress toward achieving goals.
Partnership/ Sustainability	Programs or products achieve high leverage and sustainability through intrinsic design or the involvement of appropriate local, regional, or national partners in their design, development, and dissemination.

Table 7. NASA Education Program Operating Principles [adapted from Table 3.1 of the *Earth Science Education Plan*, p. 27].

Measures

The success of NASA's education program is measured on three levels—descriptive statistics, evaluation, and performance measures. Descriptive statistics provide general information (funding levels, number and demographics of participants, etc.) about the overall program and specific activities. Individual projects provide internal evaluations to gauge project performance and assess student learning, while Education Program evaluation activities ensure compliance of individual projects with NASA education program operating principles. Performance measures that are routinely collected include information on program accessibility, partnerships, and community-recognition awards.

Relationship with NASA's Outreach Program

There is a natural and inherent link between education and outreach. While both of these elements have unique implementation plans, education and outreach are mutually supportive towards achievement of Agency goals, objectives, and outcomes. Education is concerned with what is being delivered, how it is being delivered, and the specific learning that takes place. Outreach is concerned with informing targeted audiences about what the Agency is accomplishing and learning, why it is doing so, and how Agency activities are relevant to them.

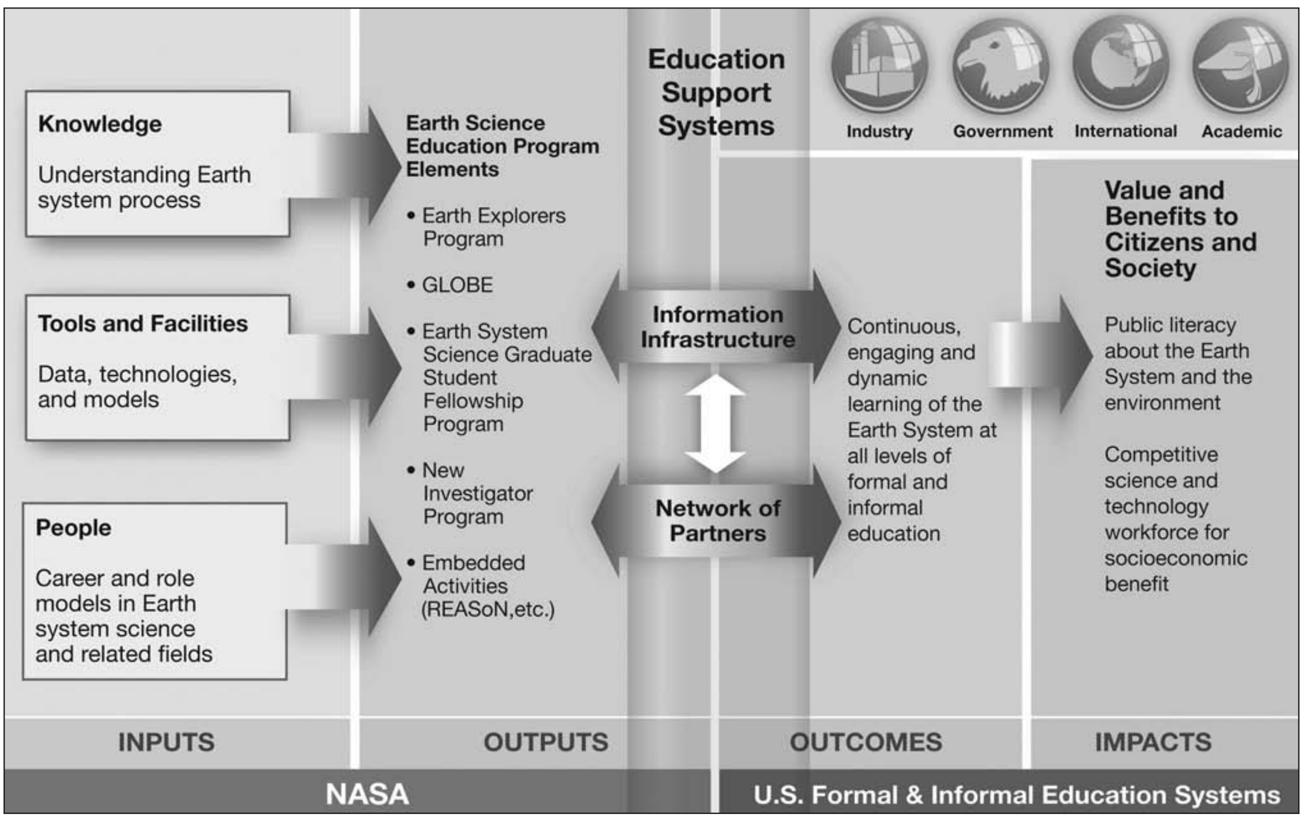


Figure 9. Earth Science Education Program Approach [adapted from Table 3.2 of the *Earth Science Education Plan*, p. 27].

Technology Program

Introduction

NASA's Science Mission Directorate conducts a technology program that develops advanced technical capabilities for future NASA Earth science and applications systems. Advanced technologies provide the foundation for a new generation of sensors, instruments, information systems, and high-end modeling frameworks. When infused into mission systems, new technologies yield improvements in our ability to observe, process, and disseminate data and information products to NASA customers.

The Earth Science Technology Office (ESTO) is responsible for development of a comprehensive technology-investment portfolio that meets the Directorate's needs. A crucial part of this role is the integration of NASA technology-management and strategic-planning activities into a single program that maintains an effective balance of the overall technology investment. This role also includes fostering cooperative relationships with internal NASA programs and partnering with other Federal agencies, academia, and private industry.

Goals and Objectives

Using NASA Earth Science needs as the focal point, ESTO identifies promising scientific and engineering concepts and supports their development. ESTO identifies capability needs from NASA science objectives and maintains traceable links between these needs and technologies in the investment portfolio. These activities are implemented through a process whereby ESTO:

- **Plans** observing systems and information and computing-system technology investments based on annual needs reviews held in collaboration with the Earth Science community. These activities identify specific technology needs that drive the focus of technology solicitations.

- **Develops** technologies through peer-reviewed competitive solicitations using formal procurement vehicles such as NASA Research Announcements (NRAs). Progress of technology-development tasks is monitored by ESTO using an on-line tracking system.

- **Infuses** mature technologies into NASA missions and infrastructure for both space- and ground-based systems. ESTO collaborates with Earth Science program planners to identify short-, mid-, and long-term infusion opportunities for new missions.

Portfolio Planning Process

The requirements described below are the means by which development activities within ESTO are executed. Portfolio-planning activities culminate in technology solicitations whereby NASA selects proposals submitted by technology developers for funding. Requests for Proposals (RFPs) are formulated through a process that begins with a gap analysis that identifies candidate technology areas for the call, continues through selection of a specific technology-focus area for the solicitation, and ends with NASA approval and formal release of the RFP. Program elements of the Earth science technology focus areas are illustrated in Figure 11.

Earth Science Technology Program Elements

Advanced Technology Initiative (ATI)—develops new ideas and concepts, performs technical-assessment studies, and supports planning of architectures, systems, and component technologies for advanced observing systems.

Instrument Incubator Program (IIP)—develops new instrument and measurement techniques. This element includes laboratory development and airborne validation of new measurement systems.

Advanced Information Systems Technology (AIST)—develops innovative on-orbit and ground capabilities for communication, processing, managing of data, and the efficient dissemination of information products.

Investment Portfolio

Program-element solicitations are conducted on a bi-annual basis. These solicitations have covered a variety of topics as illustrated in Table 8.

Current Technology Challenges for Future NASA Earth Science Programs

- Active remote-sensing sensors to enable atmospheric, cryospheric, and Earth-surface measurements.
- Large deployable apertures to enable global-weather, climate, and natural-hazards measurements from geosynchronous orbits.
- Intelligent distributed observing systems using advanced communication, onboard reprogrammable processors, autonomous network control, data compression, and high-density storage.
- Integrated modeling systems with automated information processing and knowledge-capture capabilities, data fusion, and 3-D visualization techniques.

References

NASA, 2003: *Earth Science Enterprise Strategy, October 2003*. NASA Headquarters, Code Y, 300 E Street, SW, Washington, DC 20546. [Available online at: earth.nasa.gov/visions/.]

NASA Earth Science Technology Office:
esto.nasa.gov/

NRA Solicitations	Year	Focus
IIP Round 1 (Instruments)	1998	Open and unconstrained, covering active and passive optical and active and passive microwave instruments
IIP Round 2 (Instruments)	2001	Microwave radiometry, radar, laser/lidar instruments
IIP Round 3 (Instruments)	2002	Topography & surface change, Gravity-field measurements, sea ice thickness, snow cover, GEO (tropospheric profiles, atmosphere-temperature-moisture and rainfall, coastal region), libration points L1 or L2 innovation
ATI Component Technology (ACT Round 1)	1999	Core-instrument technology, covering active and passive optical and active and passive microwave instrument components
ACT Round 2 (Components)	2002	Antenna, electronics, detectors, and optics components
AIST Round 1 (Info Systems)	1999	On-board space-based information systems applications including data processing, organization, analysis, storage, and transmission; intelligent sensor and platform control; and network configuration
AIST Round 2 (Info Systems)	2002	Space/Ground-based Computational Technology
NMP EO-1 (Space Validation)	1996	Validate technologies contributing to cost reduction and increased capabilities for future land-imaging missions (Landsat data)
NMP EO-3 (Space Validation)	1998	Validate technologies contributing to cost reduction and increased capabilities for future weather forecasting (future GOES)

Table 8. Investment Portfolio.

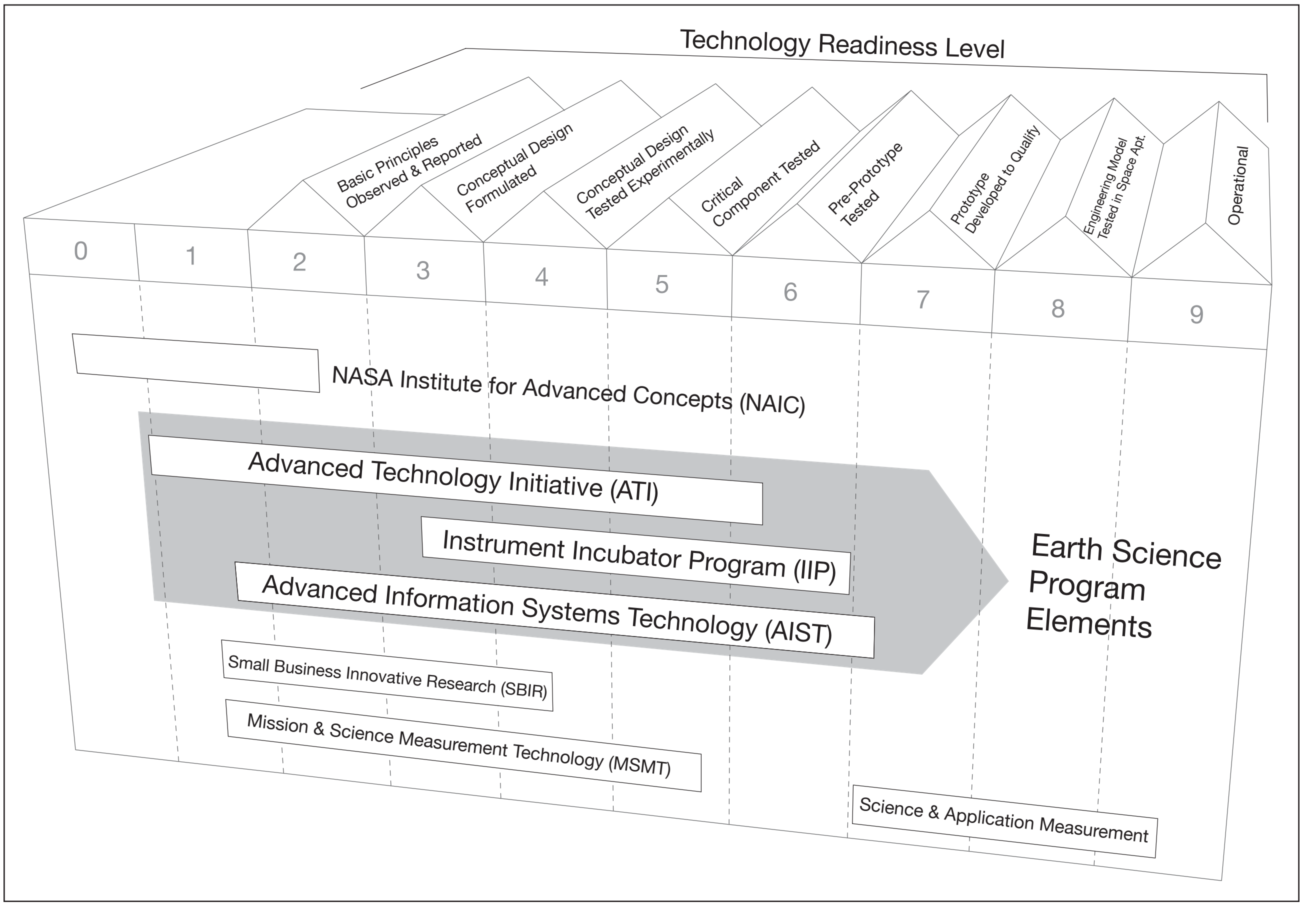


Figure 10. Program Elements of Earth Science Technology Focus Areas.

International Cooperation

NASA's Earth science missions include many important contributions from international partnerships. In order to tackle the global challenge of understanding the total Earth system, NASA relies in part on international partners who, through space agencies and other organizations, are making significant financial and hardware commitments to space-based Earth science. These international partnerships take many forms, including, for instance, NASA's providing an instrument for flight on another country's satellite and launch vehicle (or vice versa) and exchanges of scientific data resulting from independent U.S. and non-U.S. missions. The goal is to share as much useful scientific information as possible in order to answer some of the most pressing questions facing humanity today—questions about how our planet is changing and how humans are contributing to those changes. International partnerships and data sharing also promote efficiency by eliminating the need for different nations to fly multiple copies of the same (or virtually the same) scientific instrument. Furthermore, they enhance the scientific return of research missions by involving more trained minds in the analysis of the resulting scientific data.

Since its inception in 1958, NASA has sought out mutually beneficial cooperation with other nations and groups of nations in the peaceful application of its activities. Recognizing that Earth science is inherently international in its scope and function and that international cooperation is critically important to our mission, NASA currently has over 300 cooperative international agreements in Earth sciences signed since 1994. Additionally, NASA is an active participant in a number of Earth-science-related international and multilateral forums. International participation is essential to the successful achievement of NASA's goals and objectives. In order to study the various components of global change, it is necessary to gather data with a global scope and to observe and analyze phenomena that occur in different parts of the world. This requires globally dispersed test sites, ground and air campaigns, and space-based sensors. Further, the calibration and validation of space-based observations requires regional experts and *in situ* data from around the world. Finally, scientific results are most accessible and useful to different nations if their scientists and assets are part of the process of discovery.

A primary vehicle for promoting international cooperation among countries with space-based Earth observation research programs has been the Committee on Earth Observation Satellites (CEOS). CEOS brings together the space-faring nations of the world to coordinate their planned Earth observation activities, promote the sharing of data and researchers, foster the interoperability of information systems and services, and ensure the quality and accuracy of Earth observation research data through a focus on data calibration and validation. CEOS is also taking a lead in addressing the space component of a broader Integrated Global Observing Strategy (IGOS) that will encourage coordination among space and *in situ* observations. Even countries without space programs can contribute through providing access to ground-based or other *in situ* data and through analysis of the results of shared information from spacecraft. Ultimately, if the nations of the world are to take steps to address global change, they must have confidence in the research data. For that, it is important that these nations and their scientists be involved in the data production.

A top-level International Earth Observation Summit was held during July 2003 in Washington, DC. Ministerial-level representatives from thirty-three nations plus the European Commission adopted a declaration that signifies political commitment to move toward development of a comprehensive, coordinated, and sustained Earth observation system (or systems). The Earth Observation Summit attracted a distinguished group of government dignitaries from around the world who are committed to significantly advancing our collective ability to gather Earth observation data.

The Summit participants affirmed the need for timely, quality, long-term, global information as a basis for sound decision making. In order to monitor continuously the state of Earth, to increase understanding of dynamic Earth processes, to enhance prediction of the Earth system, and to carry out environmental treaty obligations, participants recognized the need for a comprehensive, coordinated, and sustained Earth observing system or systems.

To further this goal, the Summit participants launched the intergovernmental *ad hoc* Group on Earth Observations (GEO) to develop a 10-year implementation plan. The group, co-chaired by the United States, the European Commission, Japan, and South Africa and joined by more than 21 international organizations, began its work by organizing five subgroups as well as a secretariat to support its activities. The conceptual framework for a 10-year implementation plan was presented at a ministerial meeting in Tokyo in April 2004, and the plan itself was presented at an Earth Observation Summit in Brussels in February 2005.

Following the establishment of GEO, a U.S. Interagency Working Group on Earth Observations (IWGEO)

Contributing Partner	Contribution Type	Project or Instrument	Launch or Campaign Date	Vehicle
Argentina	Spacecraft, instrument, mission operations and data analysis (MO&DA)	SAC-C	November 21, 2000	Delta II
Argentina	Spacecraft, instruments MO&DA	SAC-D/Aquarius	2008	Delta II
Australia	Spacecraft, launch, instrument, MO&DA	FEDSAT	December 14, 2002	Japanese H-IIA
Belgium	Hitchhiker, ATLAS Instrument	SOLCON	3 flights flown (1997, 1998, 2003)	Space Shuttle (lost on STS-107)
Brazil	NASA aircraft overflight support and *in-situ* measurements	LBA	Ongoing 6 year Campaign	N/A
Brazil	Instrument on Aqua	HSB	May 4, 2002	Delta II
Canada	Instrument on Terra Spacecraft	MOPITT	December 18, 1999	Atlas II AS
Canada	SAR instrument/ spacecraft	RADARSAT-1	November 4, 1995	Delta II
Canada	Atmospheric Chemistry Experiment	SciSat-1	August 12, 2003	Pegasus
Canada	Cloud radar components	CloudSat	April 28, 2006	Delta II
Canada	Satellite data collection, instruments, aircraft, PIs	BOREAS	Ongoing Campaign	N/A
Central America	*In-situ* measurements, ground support	SERVIR	Ongoing Decision Support System	N/A
Denmark	Magnetic mapping payload/Oersted-2	SAC-C	November 21, 2000	Delta II
Denmark	Spacecraft, instruments, MO&DA	Oersted-1	February 23, 1999	Delta II
ESA	Provision of scientific data	ERS-1 / ERS-2	July 17, 1991 / April 21, 1995	Ariane-4
ESA	Provision of scientific data	Envisat	February 28, 2002	Ariane-5
France	Spacecraft, instruments, spacecraft operations	CALIPSO	April 28, 2006	Delta II
France	Spacecraft, instruments	TOPEX/Poseidon	August 10, 1992	Ariane-4
France	Spacecraft, instruments, validation; science	Jason-1	December 7, 2001	Delta II
France/ EUMETSAT	Spacecraft, instruments, operations, ground systems, data archival	OSTM	2008	Delta II
Germany/ France/ New Zealand	Science data analysis, validation	Orbiting Carbon Observatory (OCO)	2008	Taurus
Germany/ France	Spacecraft, launch, instrument (France)	CHAMP	July 15, 2000	Russian COSMOS

Table 9. Foreign Contributions to NASA Earth Science Satellite Missions.

Contributing Partner	Contribution Type	Project or Instrument	Launch or Campaign Date	Vehicle
Germany	MOS ocean color sensor	IRS-P3/MOS	March 21, 1996	Indian Polar Satellite Launch Vehicle
Germany	Launch, satellite operations, data downlink	GRACE	March 17, 2002	Russian Rocket
Germany	X-SAR instrument, engineering, mission operation, calibration, data processing	SRTM	February 11, 2000	Space Shuttle, STS-99
India	Access (with NOAA) to data from meteorological and remote sensors on Indian satellites and *in-situ* measurements	Earth and Atmospheric Science Cooperation	Ongoing launches and data collection	Indian Polar Satellite Launch Vehicle and Ariane
India	Spacecraft and launch	IRS-P3/MOS	March 1996	Indian Polar Satellite Launch Vehicle
Japan	Instrument on EOS Aqua	AMSR-E	May 4, 2002	Delta II
Japan	Spacecraft, instruments, launch	ADEOS I	August 17,1996	Japanese H-II
Japan	Spacecraft, instruments, launch	ADEOS II (also known as Midori II)	December 14, 2002	Japanese H-II
Japan	Spacecraft, instruments, launch	JERS	February 11, 1992	Japanese H-II
Japan	Instrument on Terra Spacecraft	ASTER	December 18, 1999	Atlas II AS
Japan	Launch, precipitation radar instrument	TRMM	November 27, 1997	Japanese H-II
Japan	Data analysis	QuikSCAT	June 19, 1999	Titan II
Japan	Launch, instruments	GPM	2011	Japanese Rocket
Netherlands	Instrument on Aura	OMI	July 15, 2004	Delta II
Russia	Spacecraft, launch	SAGE III / Meteor-3M	December 10, 2001	Russian Rocket
South Africa	Spacecraft, instruments, MO&DA	SUNSAT	February 23, 1999	Delta II
Taiwan	Microsatellites (6), instruments	COSMIC	2005	DoD
United Kingdom	Subsystems for instrument on EOS Aura	HIRDLS	July 15, 2004	Delta II
Over 30 Countries	*In-situ* data collection	Aerosol Robotic Network (AERONET)	Ongoing	N/A
Over 30 Countries	VLBI/SLR/GPS system investment and operation	NASA-led Space Geodesy Program	Ongoing	N/A

Table 9. Foreign Contributions to NASA Earth Science Satellite Missions *(cont.).*

was formed to develop a 10-year plan for implementing the United States' components of the integrated Earth Observation System.

The following paragraphs offer brief synopses of some of the major foreign contributions to NASA's Earth science efforts.

Western Europe

NASA is cooperating with the French space agency Centre National d'Etudes Spatiales (CNES) on Jason (a follow-on ocean radar altimetry mission to TOPEX/Poseidon), launched in December 2001. NASA and CNES are also cooperating on the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) mission, which was selected for development under NASA's second Earth System Science Pathfinder (ESSP-2) Announcement of Opportunity (AO). CALIPSO launched on April 28, 2006.

Cooperation between NASA and the German Aerospace Center [Deutsches Zentrum für Luft- und Raumfahrt (DLR)] includes: collection and analysis of ocean-color data from a German instrument, the Modular Optoelectronic Scanner (MOS), launched aboard the Indian Remote Sensing Satellite P3 (IRS-P3) in March 1996; the Shuttle Radar Topography Mission (SRTM), launched February 2000; the Challenging Minisatellite Payload (CHAMP), launched in July 2000; and the Gravity Recovery and Climate Experiment (GRACE) mission, launched March 2002.

The United Kingdom worked with NASA to provide the High Resolution Dynamics Limb Sounder (HIRDLS) as well as making crucial contributions to the Microwave Limb Sounder (MLS), both of which fly on Aura, launched in July 2004.

The Netherlands and Finland provided the Ozone Monitoring Instrument (OMI) for Aura. NASA arranged and funded a launch of Denmark's Oersted satellite, which included a NASA-provided Global Positioning System TurboRogue (GPS-TR) receiver. Oersted was launched in February 1999.

The European Space Agency (ESA) launched its first Earth Remote Sensing satellite (ERS-1) in 1991 and its second, ERS-2, in April 1995. NASA has agreements with ESA to receive, process, and distribute Synthetic Aperture Radar (SAR) data from both missions. ERS-1 is no longer operational, but NASA continues to receive SAR data from ERS-2. In March 2002, ESA launched its Envisat mission, which includes nine instruments to study coastal zones, oceans, ice and land surface processes, and atmospheric chemistry processes. NASA is currently working with ESA on an arrangement to receive data from Envisat-1.

Russia

On June 17, 1992, the United States and the Russian Federation signed a joint agreement concerning cooperation in the exploration and use of outer space for peaceful purposes, which has been extended through 2007. As a follow-up to this agreement, in December 1994, during meetings of the U.S.-Russian Joint Commission on Economical and Technical Cooperation (commonly known as the Gore-Chernomyrdin Commission), NASA and the Federal Space Agency of Russia (FSA) signed an implementing agreement to fly NASA's Stratospheric Aerosol and Gas Experiment III (SAGE III) aboard the Russian Meteor-3M spacecraft. For the last 35 years, the Meteor satellite series has served as a major Russian hydro-meteorological platform for environmental and natural resources (e.g., water) research. SAGE III was successfully launched on the Russian Meteor-3M spacecraft on December 10, 2001 from Baikonur, Kazakhastan, on a Zenit-2 launch vehicle. The Meteor-3M mission life requirement was for three years due to spacecraft design life limitations, while the SAGE III instrument was designed for a 5-year life. Although the mission is now in extended operations mode, the Meteor-3M satellite experienced a loss of pressure in its main canister on July 29, 2005, and some SAGE III data were lost. Although SAGE III operations resumed, the satellite may not be operational after early 2006.

In addition to SAGE III cooperation, NASA has initiated several cooperative Earth science research projects with the Russian Academy of Science (RAS), many of which contribute to EOS data calibration and validation efforts. Projects are principally in the areas of land use and land change, ecology, aerosols, and space geodesy. In particular:

Space Geodesy: NASA is currently cooperating with the Russian Academy of Sciences (RAS) and the Ukrainian Academy of Sciences in a trilateral cooperative effort in the Very Long Baseline Interferometry (VLBI) geodetic experiment. This cooperation encompasses the use of a NASA-loaned data acquisition system installed in St. Petersburg and the radiotelescope of the Crimean Astrophysical Observatory in Simeiz, Ukraine. The experiments focus on improved accuracy in VLBI measurements required for studies of Earth orientation, angular momentum, and crustal dynamics. In addition, Russia and the U.S. are cooperating on the laser tracking of satellites of mutual interest, including U.S., Russian, and Italian geodetic satellites, Russian GLONASS satellites, U.S. Global Positioning Satellites, and the U.S./French TOPEX/Poseidon oceanography satellite.

High Resolution Picture Transmission (HRPT) Stations and Advanced Very High Resolution Radiometer (AVHRR) data: This cooperative research effort has been focused on the study of boreal forests. Three NASA-loaned HRPT stations were installed in Siberia to collect 1-km resolution data from the AVHRR instrument on National Oceanic and Atmospheric Administration (NOAA) polar orbiting satellites. Raw, processed and analyzed data are available to the international science community on a full and open basis. Data from these stations have been successfully used in various satellite applications, especially for monitoring forest fires and other natural disasters.

Aerosol Robotic NETwork (AERONET): NASA has loaned several sun photometers to various Russian institutions in support of the global AERONET program. The sun photometers measure vital aerosol optical properties and water vapor, which contribute to a more-detailed understanding of global atmospheric change phenomena with a particular focus on the assessment of air quality.

Canada

NASA and the Canadian Space Agency (CSA) continue to cooperate on a variety of Earth science space missions. The Canadian RADARSAT-1 spacecraft was launched by NASA in November 1995; and CSA provided the Measurements of Pollution in the Troposphere (MOPITT) instrument for NASA's Terra mission, launched in December 1999, and the Atmospheric Chemistry Experiment (ACE) for SciSat-1, launched in August 2003.

NASA and CSA are also cooperating on the CloudSat mission, which is measuring the vertical structure of clouds from space. CSA provided the Cloud Profiling Radar Extended Interaction Klystron and RF Electronics Subsystem. CloudSat launched on April 28, 2006.

Japan

Joint Japanese/NASA Earth science activities include NASA's participation with the Japan Aerospace Exploration Agency (JAXA) on the ADEOS missions, the Tropical Rainfall Measuring Mission (TRMM), and a possible TRMM follow-on known as the Global Precipitation Measurement (GPM) mission. The Japanese Ministry of Economy, Trade and Industry (METI) also participated with NASA through its provision of the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) for NASA's Terra platform, launched in December 1999. Japan's National Space Development Agency (NASDA) provided an Advanced Microwave Scanning Radiometer-EOS (AMSR-E) for Aqua, launched in May 2002, prior to NASDA's being merged into JAXA.

The objectives of the ADEOS missions included Earth surface, atmospheric, and oceanographic remote sensing. The U.S. supplied two instruments for flight onboard ADEOS-I—a NASA Scatterometer (NSCAT) and a Total Ozone Mapping Spectrometer (TOMS). France contributed one instrument to the mission—the Polarization and Directionality of the Earth's Reflectances (POLDER). Due to technical difficulties, the ADEOS-I satellite ceased operation in June 1997, ten months after launch. ADEOS-II (also known as Midori II) was a polar-orbiting Earth observation satellite whose mission was to obtain Earth science data related to the global water cycle and the environment. ADEOS-II carried the NSCAT follow-on instrument, SeaWinds, and France's POLDER instrument, as well as Japanese instruments. ADEOS-II was launched in December 2002 and ceased functioning in October 2003.

TRMM is a joint NASA/JAXA mission to measure precipitation in Earth's tropical regions. Japan supplied the launch vehicle and precipitation radar for TRMM, and NASA provided a TRMM Microwave Imager (TMI), a Visible and Infrared Scanner (VIRS), a Clouds and the Earth's Radiant Energy System (CERES), a Lightning Imaging Sensor (LIS), and the TRMM spacecraft. TRMM was launched on a Japanese H-II launch vehicle in November 1997 and continues in operation in early 2006.

Latin America

NASA and the Argentinean Space Agency [Comisión Nacional de Actividades Espaciales (CONAE)] are working together on the Satelite de Aplicaciones Cientificas-C (SAC-C), launched in November 2000 on a NASA-provided expendable launch vehicle. SAC-C is one of a suite of satellites to carry a new GPS receiver, provided by NASA, for atmospheric, oceanic, and spacecraft navigation studies.

Following on the success of SAC-C, NASA and CONAE have agreed to cooperate on the Aquarius/Satelite de Aplicaciones Cientificas D (SAC-D) Satellite Mission. Aquarius will provide global maps of salt concentration, measuring variations in salinity to determine how the ocean responds to the combined effects of evaporation and precipitation, ice melt, and river runoff on seasonal and interannual time scales. This is critical information to understand how salinity variations modify ocean circulation and the global redistribution of heat.

Brazil provided the Humidity Sounder for Brazil (HSB) instrument for flight on NASA's Aqua mission, launched in May 2002. The HSB is a measurement system for atmospheric humidity and contributed to the enhancement of meteorological and climatic forecasts. The HSB instrument experienced an anomaly in February 2003 and has not yet been successfully restarted.

NASA is leading the U.S. science participation in the Brazilian-led Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA). LBA is a multi-disciplinary, international research effort designed to increase our understanding of the climatological, ecological, biogeochemical, and hydrological functioning of Amazonia, its interaction with other parts of the Earth system, and its response to land use change. LBA combines newly developed analytical tools (satellite and airborne remote sensing, Geographic Information System, and state-of-the-art models) and innovative, multidisciplinary, experimental designs in a powerful synthesis that will create new knowledge to address long-standing scientific issues and controversies.

In 1998, NASA joined with the Central American Commission for Environment and Development (CCAD: Comision Centro Americana de Ambiente y Desarrollo) to cooperate in establishing the Mesoamerican Biological Corridor. The Corridor links hundreds of protected areas from Mexico to Colombia, in the belief that the conservation of the region's remarkably rich biological diversity is vital for the sustainable economic development of its peoples. This partnership combines NASA's expertise in space-based observation with the intimate knowledge of local ecosystems held by a multinational cadre of Central American researchers.

As a result of the successful collaboration between NASA and CCAD, NASA expanded its efforts in the region in 2002/2003 by joining forces with the U.S. Agency for International Development and the World Bank to develop an advanced decision support system for Mesoamerica. This decision support system, named SERVIR, the Spanish acronym for the Regional Visualization and Monitoring System for Mesoamerica, will be used by scientists, educators, and policy makers to monitor and forecast ecological changes, respond to natural disasters (earthquakes, hurricanes, drought, and volcanic eruptions), and better understand both natural and human induced effects upon the regional climate.

India

In December 1997, NASA, the National Oceanic and Atmospheric Administration, India's Department of Space, and India's Department of Science and Technology signed a Memorandum of Understanding for Scientific Cooperation in the areas of Earth and Atmospheric Sciences. This agreement initiated a long-awaited Earth and atmospheric scientific cooperation between these four agencies and established communication lines for the exchange of Earth science data between India and the United States.

Under the agreement, the India Meteorological Department joined the international effort to calibrate and validate Tropical Rainfall Measuring Mission (TRMM) data and has provided important rainfall data over the Indian subcontinent for this purpose.

Australia and New Zealand

Australia is supporting an EOS Interdisclipinary Science Investigation and surface validation sites. In addition, Australia is supporting two scientists as members of the MODIS science team. New Zealand also supports EOS validation activities, in collaboration with the University of Denver.

Interagency Coordination

NASA's Science Mission Directorate has many partnerships with Federal agencies affiliated with the U.S. Climate Change Science Program (CCSP) and the U.S. Climate Change Technology Program (CCTP). The broad goals of these programs are the advancement of Earth system science and its application to societal concerns. Also, the Directorate's Applied Sciences Program conducts projects in partnership with Federal agencies that use NASA research and information to improve the delivery of the essential services these agencies provide to the nation. These partnerships are coordinated through committees or working groups that establish the tasks to be accomplished by each partner, through joint solicitations for research and development activities, and through implementation mechanisms.

NASA's Role in U.S. Climate Change Science and Technology Programs

In February 2002, the President created a new Cabinet-level management structure, the Committee on Climate Change Science and Technology Integration, to oversee the full scope of Federal climate-change research and technology development. Within this structure, CCSP integrates research and related activities sponsored by the U.S. Departments of Agriculture (USDA), Commerce (DOC), Defense (DoD), Energy (DOE), Health and Human Services (HHS), Homeland Security (DHS), Interior (DOI), State (DOS), and Transportation (DOT), as well as the Environmental Protection Agency (EPA), NASA, National Science Foundation (NSF), Smithsonian Institution (SI), U.S. Agency for International Development (USAID), Office of Science and Technology Policy (OSTP), and Office of Management and Budget (OMB).

The Director of the Climate Change Science Program Office (CCSPO) is the Assistant Secretary of Commerce for Oceans and Atmosphere. CCSP encompasses the Climate Change Research Initiative (CCRI) and the U.S. Global Change Research Program (USGCRP). CCSPO has produced a vision document and strategic plan that can be accessed at www.climatescience.gov.

CCTP is within DOE, and includes the same member agencies as CCSP (with the exception of SI). CCTP is built upon six interagency working groups. NASA chairs the Measurement and Monitoring Working Group.

NASA's Technology Program is designed to foster the creation and infusion of new technologies into NASA missions in order to enable new science observations or reduce the cost of current observations. Requirements for advanced-technology development are based on requirements that are articulated in the *Earth Science Enterprise Strategy* and accessible at: science.hq.nasa.gov/strategy/index.html. As shown in the *Strategy* document and in Tables 10–12, NASA's Earth system science research paradigm, program elements, and science focus areas are well aligned with CCSP research goals, core approaches, and research elements.

Interagency Working Group on Earth Observations (IWGEO)—During the International Earth Observation Summit of July 31, 2003, the intergovernmental ad hoc Group on Earth Observations (GEO) was formed to develop a 10-year plan for implementing an integrated Earth Observation System (details are given in the International Cooperation section). Subsequently, a U.S. Interagency Working Group on Earth Observations (IWGEO) was formed to develop a 10-year plan for implementing the U.S. components of the integrated Earth Observation System.

The roles and responsibilities of the IWGEO are to:

- develop a U.S. National Plan for the Earth Observation System;
- coordinate with Academia and the Private Sector;
- formulate the U.S. Position and Input to the GEO; and
- coordinate with Standards Bodies on Data Quality and Data Management.

The IWGEO is co-chaired by Ghassem Asrar (NASA), Cliff Gabriel (OSTP), and Greg Withee [National Oceanic and Atmospheric Administration (NOAA)]. It comprises representatives from 15 member agencies: DHS, DOC, DOE, DOT, EPA, HHS, NASA, DoD, NSF, OSTP, SI, DOS, USDA, USAID, and the United States Geological Survey (USGS). IWGEO is structured to mirror GEO. Along with an executive secretariat and a planning and integration team, IWGEO contains architecture, data utilization, user requirements and outreach, capacity building, and international cooperation teams.

GOES and POES Environmental Satellite Program—The Geostationary Operational Environmental Satellite (GOES)/Polar-orbiting Operational Environmental Satellite (POES) program is a cooperative effort between NASA and NOAA. NASA's Goddard Space Flight Center (GSFC) is responsible for the construction, integration and launch of NOAA satellites. Operational control of each spacecraft is turned over to NOAA after the spacecraft is checked out on orbit.

The GOES/POES mission is composed of two geostationary satellites and two polar orbiting satellites. These satellites operate in pairs. The geostationary satellites, GOES-East covering the U.S. east coast and GOES-West covering the U.S. west coast, provide real-time weather data for use in short-term weather forecasting (warnings of severe weather) and space environment monitoring, as well as research and development. The two POES polar orbiting satellites are sun-synchronous, one with a morning equatorial-crossing time and the other with an afternoon crossing time. Operating as a pair, these satellites ensure that the most recent data for any region of the U.S. are no more than six hours old.

National Polar-orbiting Operational Environmental Satellite System (NPOESS)—NASA participates with U.S. operational satellite agencies (NOAA and DoD) in the Integrated Program Office (IPO) for NPOESS that is planned to become operational toward the end of this decade. NPOESS will replace the present NOAA polar environmental satellites and the DoD polar meteorological satellites. NASA's goal is to ensure the long-term continuity of key environmental measurements. NASA promotes the convergence of the operational observation requirements of partner agencies with its own research data needs for systematic observations, shares the cost of new developments, and develops precursor instruments and spacecraft technologies for future operational application missions. NASA also encourages the continuing involvement of scientific investigators in the calibration and validation of operational measurements, the development of more-advanced information retrieval algorithms, and the analysis of operational data records.

The NPOESS Preparatory Project (NPP), planned for launch in 2008, is a joint NASA/IPO mission to extend key measurements in support of long-term monitoring of climate trends and of global biological productivity. It will extend the measurement series being initiated with EOS Terra and Aqua and provide a bridge between NASA's EOS missions and NPOESS. The NPP mission will also provide operational agencies early access to the next generation of operational sensors, thereby greatly reducing the risks incurred during the transition.

Earth System Modeling Framework (ESMF)—The NASA Earth Science Technology Office (ESTO) has established the Earth System Modeling Framework (ESMF). ESMF consists of Earth scientists and computational experts from major U.S. Earth modeling centers and is developing a robust, flexible set of software tools to enhance ease of use, performance portability, interoperability, and reuse in climate, numerical weather prediction, and data-assimilation applications. A multi-agency collaboration that includes many of the major climate, weather, and data assimilation efforts in the U.S. is responsible for developing ESMF. The collaboration includes activities sponsored by NSF, NOAA, DOE, NASA, and over a dozen universities.

U.S. Weather Research Program (USWRP)—NASA is a major participant in the multi-agency (NOAA, NSF, NASA, DOT, DOE, USDA, DoD, EPA) U.S. Weather Research Program (USWRP). The goal of NASA's participation is to contribute to the improvement of near-term forecasts through NASA's latest remote-sensing, data-analysis, and modeling research. Understanding and predicting the occurrence of high-impact (severe and hazardous) weather events are highlighted within the NASA Earth Science Enterprise Research Strategy for Mesoscale Weather Observations and Research and are principal scientific objectives of USWRP.

EarthScope—EarthScope is a multi-agency program for fundamental and applied research throughout the U.S. that will contribute to mitigating risks from geological hazards, developing natural resources, and improving the public's understanding of the dynamic Earth. A key component of EarthScope is the Interferometric Synthetic Aperture Radar (InSAR), a dedicated satellite mission carried out jointly between NASA, NSF, and USGS that will provide spatially continuous Earth-strain measurements over wide geographic areas. NASA will play a leading role in the InSAR mission.

NASA Applied Sciences Program

In addition to the activities described above, NASA's Applied Sciences Program (described in detail in the Applied Sciences Program section) relies heavily on forging partnerships with other Federal agencies to accomplish its objectives. NASA chooses to partner with those agencies that have pre-existing connections with end-users, information infrastructure already in place, and decision support systems that can be enhanced by Earth science information, which NASA is uniquely poised to provide.

As examples, the Federal Aviation Administration (FAA) works with the aviation industry to deliver the benefits of the National Airspace System to travelers. NASA supports that system with atmospheric observations and predictions and with synthetic vision technologies. Likewise, the Federal Emergency Management Agency (FEMA) provides state, local, and tribal emergency managers with earthquake risk assessments using the Hazards U.S. (HAZUS) model. NASA helps FEMA improve HAZUS with topography, land-cover change, and related

CCSP Research Goals	NASA Earth Science Research Questions
Improve knowledge of Earth's past and present climate and environment, including its natural variability, and improve understanding of causes of observed variability and change	How is the global Earth system changing? (Variability)
Improve quantification of the forces bringing about changes in Earth's climate and related systems	What are the primary causes of change in the Earth system? (Forcings)
Reduce uncertainty in projections of how Earth's climate and related systems may change in the future	How does the Earth system respond to natural and human-induced changes? (Response)
Understand the sensitivity and adaptability of different natural and managed ecosystems and human systems to climate and related global changes	What are the consequences of change in the Earth system for human civilization? (Consequences)
Explore the uses and identify the limits of evolving knowledge to manage risks and opportunities related to climate variability and change	How will the Earth system change in the future? (Prediction)

Table 10. CCSP Research Goals and associated NASA Earth Science Research Questions.

CCSP Core Approaches	NASA Earth Science Programs
Scientific Research	Research
Observations and Data Management	Observations and Information Systems
Decision Support	Applied Sciences
	Technology
Communications	Education

Table 11. CCSP Core Approaches and associated NASA Earth Science Programs.

CCSP Research Elements	NASA Earth Science Research Focus Areas
Climate Variability and Change	Climate Variability and Change
Atmospheric Composition	Atmospheric Composition
Land Use / Land Cover Change Global Carbon Cycle Ecosystems	Carbon Cycle, Ecosystems, and Biogeochemistry
Global Water Cycle	Water and Energy Cycles
Human Contributions and Response	
	Weather
	Earth Surface and Interior

Table 12. CCSP Research Elements and associated NASA Earth Science Research Focus Areas.

data. NASA collaborates with these agencies as well as with a host of others (see Table 6 in the Applied Sciences Program section) on its twelve Applied Science Program Elements. The goal is to benchmark the capacity of Earth science research to improve these other agencies' decision support tools so they can better serve the entire nation.

References

NASA, 2003: *Earth Science Enterprise Strategy, October 2003*. NASA Headquarters, Washington, DC, 94 pp. [Available online at: science.hq.nasa.gov/strategy/index.html.]

NASA's Earth Observing Missions

Studying the Earth System from Space

Since its founding back in 1958, NASA has been planning and launching missions to study the Earth from space. From the 1960s through the 1980s technology was developed to view the Earth globally, focusing on individual components of the Earth system. This launched an era of rich scientific discovery, including participation in the discovery of the processes behind Antarctic ozone depletion (EP/TOMS[1]), the Earth's response to incoming solar radiation (ERBS), and the extent, causes, and impacts of land use and land cover change (Landsat 7[2]).

During the decades of the 1980s and 1990s, the knowledge of the Earth system was expanded and the interdisciplinary field of Earth system science began to mature. Through satellites, NASA and others began to survey the Earth system in its entirety on a routine basis. The Earth Observing System (EOS), first conceived in the 1980s as a series of systematic measurements of the interactions among land, oceans, atmosphere, and life, began to take shape during the 1990s. Meanwhile, scientists began to use space-based observations, coupled with sub-orbital and in situ observations, to uncover the mechanisms behind the El Niño/La Niña cycle (TOPEX/Poseidon) and began to model the climate system in a meaningful way. For the first time, scientists were able to probe the upper regions of the atmosphere and study its complex chemistry (UARS) and measure the global distribution of atmospheric aerosols and related changes over seasons and years (UARS, EP/TOMS). Scientists also began to get a better handle on the distribution of global precipitation, particularly in tropical regions (TRMM), and biological activity in our oceans (Orbview-2/SeaWiFS).

The so-called 'EOS era' began in earnest with the launch of Terra in 1999. Terra serves as the flagship of the EOS program. It is a joint NASA mission with Japan and Canada that has five advanced instruments onboard, each directed at various aspects of land and ocean surfaces, sea surface temperature, cloud patterns, small atmospheric particles called aerosols, and the balance of solar energy absorbed and reflected by Earth. In 2002, Aqua joined Terra in orbit. Aqua carries a synergistic six-instrument payload designed to observe how moisture cycles between Earth's lithosphere (land), hydrosphere (water), atmosphere (air), and cryosphere (ice). Aura was the third and final major EOS mission, launched in 2004. Its mission is to study the atmosphere's chemistry and dynamics and to investigate questions about ozone trends, air quality changes, and the linkages of these changes to climate change. Aura's four instruments all contribute to the mission's goals. These three primary EOS missions are joined by a host of other more narrowly focused EOS missions, all of which are described in this expanded section.

NASA's Earth-observing satellites and sponsored research have encouraged scientists to view the Earth as a system—a dynamic set of interactions among continents, atmosphere, oceans, ice, and life. The resulting new interdisciplinary field of Earth system science is critical to understanding how global climate responds to the forces acting on it.

In addition to the EOS series of missions, NASA has a number of complementary current and planned Earth System Science Pathfinder (ESSP) missions intended to probe specific Earth processes in detail. These processes involve Earth's gravity field (GRACE), clouds (CloudSat), the interplay between clouds and aerosols (CALIPSO), carbon sources and sinks (OCO), and ocean salinity (Aquarius). NASA also launched the EO-1 mission under the New Millennium Program, focused on demonstrating new technologies for future missions.

With the successful launch of Aura in 2004, the three major EOS satellites are in orbit and the goal of having a system of satellites with the ability to characterize the current state of the Earth system has become a reality. We look to future missions to complement EOS and continue to enhance our capabilities to observe the Earth as a system and our ability to predict how the system is likely to change in the future.

NASA also partners with other government agencies to work on missions. NASA designs, develops, and launches the Nation's civilian operational environmental satellites, in both polar and geostationary orbits (POES and GOES), by agreement with the National Oceanic and Atmospheric Administration (NOAA). NOAA assumes control of these satellites after activation and provides the resulting data on a continuous basis for weather prediction and other services.

NASA's EOS, in addition to enabling global change research with advanced sensors, serves as the technology source for the next generation POES satellite. NOAA, DoD, and NASA are proceeding with the development of POES in the joint civilian/military project NPOESS and the NPOESS Preparatory Project (NPP) bridging EOS and NPOESS. NPP is a multi-instrument satellite that will extend climate change measurements begun by EOS Terra and Aqua while demonstrating new technologies for

[1] TOMS instruments previously flew on Nimbus-7 (NASA), Meteor-3 (Russia), and ADEOS (Japan). Measurements date back to 1978.

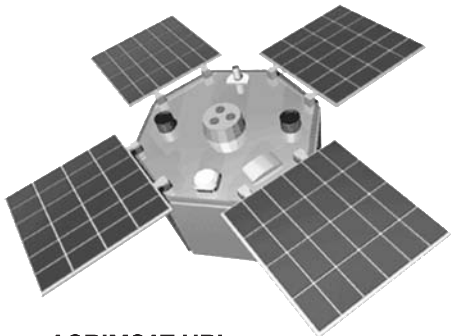
[2] A series of Landsat missions, originally named ERTS, dates back to 1972.

NPOESS. NASA and NOAA also continue to plan the next generation of GOES satellites.

In the years ahead, Earth-orbiting satellites will likely evolve into constellations of smart satellites that can be reconfigured based on the changing needs of science and technology. Beyond that, we envision an intelligent and integrated observation network composed of sensors deployed in vantage points from the subsurface to deep space. This 'sensor web' will provide on-demand data and analysis to a wide range of end users in a timely and cost-effective manner. These data and information products will be used in Earth system models by NASA and partner agencies such as NOAA, NSF, and DOE, to assess and predict Earth system change. This observation system will have many practical benefits for scientific research, national policymaking, and economic growth.

ACRIMSAT

Active Cavity Radiometer Irradiance Monitor Satellite



ACRIMSAT URLs

Science Team: www.acrim.com
Instrument Team: acrim.jpl.nasa.gov

Summary

ACRIMSAT was launched on December 20, 1999, as a secondary payload on a Taurus launch vehicle and carries the Active Cavity Radiometer Irradiance Monitor 3 (ACRIM3) instrument. The science mission began on April 5, 2000, following a period of on-orbit adjustment of the solar-pointing software on ACRIMSAT. The purpose of ACRIM3 is to study Total Solar Irradiance (TSI). ACRIM3, the third in a series of ACRIM solar-monitoring experiments built for NASA by the Jet Propulsion Laboratory (JPL), extends the database begun by ACRIM1, launched in 1980 on the Solar Maximum Mission (SMM) spacecraft, and continued by ACRIM2, launched on the Upper Atmosphere Research Satellite (UARS) in 1991. ACRIMSAT/ACRIM3 completed its five-year Minimum Mission in 2005 and recently began the second year of its Extended Mission. Spacecraft and instrument engineering vital signs indicate that operations could continue for at least another decade. The spacecraft orbit will not decay significantly for several decades.

Instrument

- Active Cavity Radiometer Irradiance Monitor (ACRIM3)

Point of Contact

- *ACRIMSAT Principal Investigator:* Richard Willson, Columbia University

Other Key Personnel

- *ACRIMSAT Program Scientist:* Don Anderson, NASA Headquarters
- *ACRIMSAT Program Executive:* Lou Schuster, NASA Headquarters

Key ACRIMSAT Facts

Orbit:

Type: Near polar, sun-synchronous
Altitude: 713 km (apogee), 672 km (perigee)
Equatorial Crossing: 10:00 a.m.
Inclination: 98°
Period: 98.6 minutes

Dimensions: 1 m^3

Downlink: Table Mountain Observatory (JPL)

Design Life: 5-year minimum lifetime

Partners

Columbia University, Center for Climate Systems Research: Science team

Jet Propulsion Laboratory: ACRIM3 instrument, ground station, satellite operation, data archiving

Orbital Sciences Corporation: ACRIMSAT satellite, Taurus launch vehicle

Langley Research Center (LaRC), Distributed Active Archive Center (DAAC): Archive of ACRIM3 results

Mission Type

Earth Observing System (EOS) Systematic Measurements

Launch and Location

- *Date and Location:* December 20, 1999, from Vandenberg Air Force Base, California
- *Vehicle:* Taurus

Relevant Science Focus Areas

(see NASA's Earth Science Program section)

- Climate Variability and Change
- Water and Energy Cycles

Related Applications

(see Applied Sciences Program section)

- Carbon Management
- Energy Management
- Public Health

ACRIMSAT Science Goals

- Extend the TSI observational database with maximum precision and traceability.

- Continue the TSI monitoring precision-overlap measurement paradigm to relate past and future TSI databases through ACRIM3 results using comparisons with the UARS/ACRIM2 experiment, the Solar Heliospheric Observatory (SOHO)/Variability of Solar Irradiance and Gravity Oscillations (VIRGO) experiment, and the Solar Radiation and Climate Experiment (SORCE)/Total Irradiance Monitor (TIM) experiment.

- Develop a composite TSI time series incorporating results from satellite TSI observations since 1978.

- Investigate the multi-decadal upward TSI trend during solar cycles 21–23 using ACRIM3 observations of the solar activity minimum preceding cycle 24.

- Provide a redundant monitoring capability in an extended mission to prevent catastrophic loss of the TSI long-term database in the event of the failure of the SORCE/TIM experiment.

ACRIMSAT Mission Background

Sustained changes in the TSI of as little as a few tenths of one percent per century could be important causal factors for significant climate change. It is clear from paleo-climate research that solar-irradiance-driven climate changes have occurred in the past. There is compelling evidence that some of these may have been at least partially driven by intrinsic solar variability. A precise, long-term record of TSI is required to provide empirical evidence of the Sun's role in climate change and to separate its effect from other climate forcings such as greenhouse warming. The same record, together with other solar observations, will also yield an improved understanding of the physics of the Sun and the causes of luminosity variations, and could eventually lead to a predictive capability for solar-driven climate change.

In 1994, the National Research Council published its findings regarding research priorities for "Solar Influences on Global Change," one of the seven science elements of the U.S. Global Change Research Program (USGCRP). Its recommendations include "monitoring total and spectral solar irradiance from an uninterrupted, overlapping series of spacecraft radiometers employing in-flight sensitivity tracking" as this element's highest priority and most urgent activity. The ACRIMSAT/ACRIM3 experiment is designed to be a cost-effective, small-satellite approach to meeting the total solar irradiance priority during the first phase of the Earth Observing System (EOS) program.

There is a contiguous satellite TSI observational database extending over the past 25+ years with useful precision for solar physics and climatology investigations. A composite TSI database can be constructed from this database by reconciling published results from the Nimbus-7/Earth Radiation Budget (ERB), SMM/ACRIM1, UARS/ACRIM2, and ACRIMSAT/ACRIM3 experiments to a common scale, using overlapping comparisons. Key to this process is determining the relationship of the results of the non-overlapping ACRIM1 and ACRIM2 experiments. The ACRIM composite approach, which reconciles the unmodified results published by the science teams of each experiment to the ACRIM3 scale, demonstrates a resolved + 0.04 (± 0.01) %/decade trend between the solar minima of 1986 and 1996, using the Nimbus-7/ERB data to relate ACRIM1 & 2 results.

Observations by ACRIM and other satellite experiments have established the Sun as a variable star. Its luminosity varies by more than 0.3% during the passage of large sunspot groups across the visible side of the Sun (1 week–10 days) and by 0.1% over a solar cycle in phase with the level of solar magnetic activity (10–11 years). It demonstrates a secular trend at a rate of +0.04% per decade between the solar cycle minima in 1986 and 1996, the physical cause of which has yet to be discovered. Photometric observations of many solar-type stars have revealed that brightness variations correlated with magnetic activity like the Sun's are a common phenomenon. Many solar-type stars demonstrate higher variability than the Sun, leading to speculation that the Sun's variability may have been greater in the past and may be greater again in the future. The 0.04%/decade trend during solar cycles 21–23 is supported by recent findings by solar physicists observing similar trends in other luminosity-dependent phenomena. This would clearly have significant implications for climate change.

The lifetimes of previous ACRIM experiments, designed for 18-month-minimum missions, have averaged nearly 10 years (e.g., UARS/ACRIM2 acquired science data from October 4, 1991 through November 1, 2001). ACRIM3, designed to meet the EOS 5-year-minimum mission requirement, has already exceeded that by over a year and indications from analyses of ACRIMSAT/ACRIM3 satellite, instrument, and orbit data are that it could function without loss of data quality for at least another decade. The ACRIM3 experiment began its extended mission in 2005 and it is hoped that it will be able to continue well through the next solar-activity minimum between the solar maxima of cycles 23 and 24.

The SORCE satellite carrying the TIM instrument, launched in 2003, will pick up the thread of TSI monitoring during EOS phase 2. Overlapping comparisons will establish the relationship between TIM and ACRIM3 at the level of their mutual precisions. This is essential in sustaining the long-term TSI database at a level of traceability required for climate investigations of solar forcing, since the 'absolute' uncertainty of this technology (~0.1% in S.I. units) is insufficient. Operation of the ACRIM3 mission through at least the next solar-activity minimum (~2006) is important for the long-term TSI database for two reasons: 1) the most precise information on the nature of any long-term variation in TSI that may be of climatological significance will be most traceably resolved by extension of the ACRIM2-ACRIM3 results; and 2) the redundancy provided by coincident ACRIM3 and TIM experiments is required to prevent loss of the database in the event of the failure of one of them.

Discovery of subtle but important rates of TSI variability on solar cycle (~ 1000 ppm) and longer time scales (~ 400 ppm/decade) has made it clear that a useful long-term TSI database for climate change and solar physics should have the maximum traceability accessible using current technology. This can be provided by a measurement paradigm employing the relative precision of overlapping satellite TSI monitors, which can be smaller than 5 ppm/yr (ACRIM3 traceability is 3 ppm/yr). Comparable traceability using sensor accuracy is not possible since the 'absolute' (solar irradiance) uncertainty of the ambient temperature from sensors used in all satellite TSI experiments to date is not significantly less than ~1000 ppm. Sensors operating at liquid helium temperatures have demonstrated solar irradiance accuracy in the 100 ppm range, but this level of performance has only been realized by ground-based, laboratory instrumentation that is not practically adaptable to satellite operations.

TSI proxy models using linear regression techniques and solar emission proxies related to solar magnetic activity are not competitive in accuracy, precision, or traceability with satellite TSI observations. Regression models, misused to 'fine tune' TSI observations in some recent TSI composite time series, can actually offer only qualitative information regarding solar-luminosity variability on all time scales that is orders of magnitude inferior to even the least traceable satellite TSI observations.

The single approach capable of providing the required precision of the long-term TSI database with current measurement technology employs a redundant 'overlap strategy' in which successive ambient-temperature TSI satellite experiments are compared in flight, transferring their operational precision to the database.

ACRIM3

Active Cavity Radiometer Irradiance Monitor

ACRIM3 was designed to monitor the total solar irradiance with the highest precision and traceability accessible using current technology. It continues the state-of-the-art measurements of TSI begun with the SMM/ACRIM1 and UARS/ACRIM2 experiments. The SMM and UARS satellites were launched in 1980 and 1991, respectively.

The ACRIMSAT spacecraft was launched on December 20, 1999, into a 700-km sun-synchronous orbit with a 98° inclination. Instrument checkout and optimization of solar-pointing algorithms were carried out during January–March 2000. The science mission

Key ACRIM3 Facts

Heritage: ACRIM1 (SMM) and ACRIM2 (UARS)

Instrument Type: Active Cavity Radiometer type 4 sensors

Scan Type: Solar pointed

Solar Pointing: Spin stabilization about axis of symmetry

Calibration: By metrology of instrument optics and electronics in the Systeme Internationale (SI) (International System of Units)

Field of View: ± 2.5°

Instrument IFOV: ± 1.0°

Sampling Interval: ~2 minutes

Physical Size: 0.1 m^3

Mass: 10 kg

Power: 5 W (average)

Duty Cycle: Continuous

Data Rate: < 1 kbps

Direct Readout: No

began April 5, 2000, and has provided an average of 65 minutes of TSI data per orbit.

ACRIMSAT References

Schneider, G., J. M. Pasachoff, and R. C. Willson, 2006: The effect of the transit of Venus on ACRIM'S total solar irradiance measurements: Implications for transit studies of extrasolar planets. *The Astrophysical Journal*, **641**, 565–571.

Willson, R. C., 1979: The Active Cavity Radiometer Type IV. *Appl. Opt.*, **18**, 179–188.

Willson, R. C., 1994: Irradiance observations of SMM, Spacelab 1, UARS and ATLAS experiments, in J. Pap, C. Frohlich, H. Hudson and K. Solanki, eds., *The Sun as a Variable Star*, IAU Col.143 proc., Cambridge University Press, 54–62.

Willson, R. C., 1997: Total solar irradiance trend during solar cycles 21 and 22. *Science*, **277**, 1963–1965.

Willson, R. C., 2001: The ACRIMSAT/ACRIM3 experiment—extending the precision, long-term Total Solar Irradiance climate database. *The Earth Observer*, **13**, 14–17.

Willson, R. C., and A. V. Mordvinov, 2003: Secular Total Solar Irradiance trend during solar cycles 21–23. *Geophys. Res. Letters*, **30**, 1199–1202.

Willson, R. C., S. Gulkis, M Janssen, H. S. Hudson, and G. A. Chapman, 1981: Observations of solar irradiance variability. *Science*, **211**, 700–702.

Willson, R. C., H. S. Hudson, C. Frohlich, and R. W. Brusa, 1986: Long-term downward trend in total solar irradiance. *Science*, **234**, 1114–1117.

Willson, R. C., and H. S. Hudson, 1991: The Sun's luminosity over a complete solar cycle. *Nature*, **351**, 42–44.

Willson, R. C., and H. S. Hudson, 1998: Solar luminosity variations in solar cycle 21. *Nature*, **32**, 810–812.

National Research Council, 1994: *Solar influences on climate change*. National Academy Press, Washington, D.C., 180 pp.

ACRIMSAT Data Products

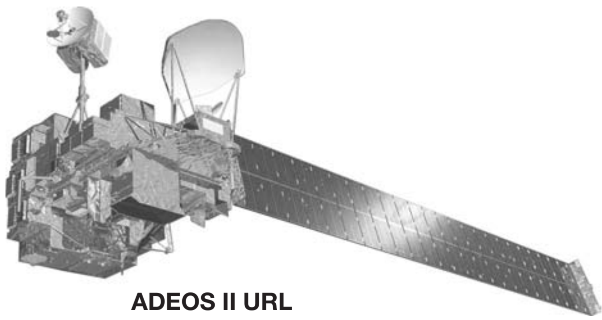
For more information about the data products please see EOS Data Products Handbook, Volume 2 available at: eospso.gsfc.nasa.gov/eos_homepage/for_scientists/data_products/.

Product Name or Grouping	Processing Level	Coverage	Browse Available
ACRIM3 Instrument *Data Set Start Date: April 5, 2000*			
Radiometric Products	1, 2	~2 minutes	Daily solar irradiance graphs

ACRIMSAT Data Products

ADEOS II

Advanced Earth Observing Satellite II



ADEOS II URL
sharaku.eorc.jaxa.go.jp/ADEOS2

Key ADEOS II Facts

Joint with Japan and France

Orbit:
Type: Near polar, sun-synchronous
Equatorial Crossing: 10:15 a.m.
Altitude: 803 km
Inclination: 98.6°
Period: 101 minutes
Repeat Cycle: 57 orbits (~4 days)

Dimensions: 4 m × 4 m × 6 m (spacecraft), 3 m × 24 m solar panel, with panel deployed, 7 m in-flight direction, 29 m perpendicular

Mass: 3680 kg at launch

Power: 5000 W

Downlink: 468.875 MHz at 4 Mbps. Cross-link to Data Relay Test Satellite (DRTS) at Ka-band, 120 Mbps

Design Life: Designed for 3-year mission, failed after 10 months

Contributor: JAXA built and operated ADEOS II

Summary

The ADEOS II mission was an international satellite mission led by the Japan Aerospace Exploration Agency (JAXA)—formerly the National Space Development Agency (NASDA) of Japan—with U.S. (NASA) and French Centre Nationale d'Etudes Spatiales (CNES) participation. Midori-II is the Japanese name for the mission.

The ADEOS II mission ended prematurely ten months after launch, owing to a failure of the solar panel on October 24, 2003.

Instruments

- Advanced Microwave Scanning Radiometer (AMSR)
- Global Imager (GLI)
- Improved Limb Atmospheric Spectrometer-II (ILAS-II)
- Polarization and Directionality of the Earth's Reflectances (POLDER)
- SeaWinds

Points of Contact

- *ADEOS II Program Scientist:* Akimasa Sumi, University of Tokyo
- *SeaWinds Project Scientist:* Timothy Liu, NASA Jet Propulsion Laboratory/California Institute of Technology

Mission Type

Earth Observing System (EOS) Systematic Measurements

Launch and Location

Date and Location: December 14, 2002, from Tanegashima Space Center, Japan

Vehicle: H-IIA launch vehicle No. 4

Relevant Science Focus Areas

(see NASA's Earth Science Program section)

- Climate Variability and Change
- Weather

Related Applications

(see Applied Sciences Program section)

- Air Quality
- Coastal Management
- Disaster Management

ADEOS II Science Goals

- Monitoring the water and energy cycle as a part of the global climate system.
- Quantitatively estimate the biomass and fundamental productivity as a part of the carbon cycle, which plays an important role in global warming.

- Detect trends in long-term climate change as a result of continuing the observations started by ADEOS-I.

ADEOS II Mission Background

ADEOS II was the successor to ADEOS [Midori], designed to advance Earth-observation technologies. The mission was launched on December 14, 2002. Regrettably, the spacecraft's solar panel failed on October 24, 2003. Although the mission was short-lived, the data collected will help researchers better understand global environmental changes such as global warming. ADEOS II has provided data that helps us better understand the circulation of water, energy, and carbon in order to contribute to studies on global environmental changes.

ADEOS II was equipped with two JAXA sensors: the Advanced Microwave Scanning Radiometer (AMSR) for quantitatively observing various geophysical data concerning the water cycle, and the Global Imager (GLI) for observing oceans, land, and the atmosphere with high accuracy. It also carried three sensors provided by international and domestic partners.

Instrument Descriptions

Despite the spacecraft failure, brief descriptions are included for each instrument on ADEOS II. SeaWinds was the only NASA Earth Observing System (EOS) instrument, and hence Key Facts and Data Products boxes are provided only for SeaWinds.

AMSR

Advanced Microwave Scanning Radiometer

AMSR detects microwave emissions from Earth's surface and atmosphere. Various geophysical parameters, particularly those related to atmospheric water (H_2O), sea surface wind speed and temperature, and sea ice type and extent can be estimated from AMSR data. In addition to the proven parameters, such as integrated atmospheric water vapor and liquid water, precipitation rate, sea surface wind speed, and all-weather sea surface temperature (SST), novel geophysical parameters, including soil moisture, could be retrieved by using AMSR's low-frequency channels.

AMSR is an eight-frequency, total-power microwave radiometer with dual polarization (except two vertical channels in the 50 GHz band). Conical scanning is employed to observe Earth's surface with a constant incidence angle. Calibration counts are obtained every scan by using the hot-load target (around 300 K) and the cold-sky mirror to introduce the temperature of deep space (around 3 K). The offset-parabolic antenna with a diameter of 2 m is the largest spaceborne microwave radiometer antenna of its kind. A superior spatial resolution enables us not only to resolve small-scale features, including clouds, precipitation, sea ice, and land, but also to improve retrieval accuracy of geophysical parameters.

More details on AMSR can be found under the Aqua Mission description. Aqua carries a similar instrument called AMSR-E.

AMSR URL

sharaku.eorc.jaxa.jp/AMSR/index_e.htm

AMSR Science Team Leader

Akira Shibata, Earth Observation Research Center, JAXA

GLI

Global Imager

GLI is an optical sensor that observes the reflected solar radiation from Earth's surface, including land, oceans, and atmosphere and/or infrared radiation with a multi-channel system for measuring the biological content, such as chlorophyll, organic substance, and vegetation index as well as temperature, snow and ice, and cloud and aerosol distribution. These data will be used for understanding the global circulation of carbon and climate changes.

GLI URL

sharaku.eorc.jaxa.jp/ADEOS2

GLI Science Team Leader

Teruyuki Nakajima, University of Tokyo

ILAS

Improved Limb Atmospheric Spectrometer-II

ILAS-II was developed by the Ministry of the Environment to monitor high-latitude stratospheric ozone. The objectives of ILAS-II are to monitor and study changes in the stratosphere triggered by emissions of chlorofluorocarbons (CFCs) and to evaluate the effectiveness of worldwide emission controls of CFCs. ILAS-II is a spectrometer that observes the atmospheric limb absorption spectrum from the upper troposphere to the stratosphere, using sunlight as a light source (solar-occultation technique). The spectrometer covers the infrared region (3–13 μm) and the near-visible region (753–784 nm). ILAS-II was designed to improve observation accuracy and cover wider spectral ranges than ILAS, which was based on the Limb Atmospheric Spectrometer (LAS) aboard EXOS-C (Ohzora, ISAS, 1984). ILAS-II observations are focused on the high latitudes (56–70°N, 63–88°S) because of the geometrical relation of the solar-occultation events with the sun-synchronous orbit. From these spectral observations, ILAS-II can measure the vertical profiles of species related to ozone depletion, including ozone (O_3), nitrogen dioxide (NO_2), nitric acid (HNO_3), aerosols, water vapor (H_2O), CFC-11, CFC-12, methane (CH_4), nitrous oxide (N_2O), chlorine nitrate ($ClONO_2$), and temperature and pressure.

ILAS-II URL

www-ilas2.nies.go.jp/en

ILAS-II Principal Investigator

Yasuhiro Sasano, National Institute for Environmental Studies

POLDER

Polarization and Directionality of the Earth's Reflectances

POLDER observes the polarization, directional, and spectral characteristics of the solar light reflected by aerosols, clouds, oceans, and land surfaces.

POLDER is a 2-dimensional charge-coupled device (CCD) array, with a wide field of view, multi-band imaging radiometer and polarimeter developed by CNES. Multi-angle viewing is achieved by the along-track migration, at the spacecraft velocity, of a quasi-square footprint intercepted by the total instantaneous ±43° × ±51° wide field of view. This footprint is partitioned into 242 × 274 elements of quasi-constant 7-km × 6-km resolution, imaged by a CCD matrix in the focal plane. Simultaneously, a filter and polarizer wheel rotate and scan eight narrow spectral bands in the visible and near infrared (443, 490, 564, 670, 763, 765, 865, and 910 nm).

POLDER URL

smsc.cnes.fr/POLDER

SeaWinds

NASA's SeaWinds Scatterometer provided high-accuracy, near-all-weather surface wind speed and direction measurements over at least 90% of the ice-free global oceans every two days. SeaWinds on ADEOS II contributed to the long-term wind data set for studies of ocean circulation, climate, air-sea interaction, and weather

Key SeaWinds Facts

Heritage: SeaSat, NSCAT

Dimensions:

CDS: 32 cm × 46 cm × 34 cm

SES: 81 cm × 91 cm × 43 cm

SAS: ~150 cm; 100-cm diameter antenna dish on 60-cm diameter × 60-cm pedestal

Mass: 220 kg

Power: 220 W

Duty Cycle: 100%

Data Rate: 40 kbps

Thermal Control: Radiators

Thermal Operating Range: 5–40° C

Field of View (FOV): Rotating (at 18 rpm) pencil-beam antenna with dual feeds pointing 40° and 46° from nadir

IFOV: ± 51° from nadir

Swath: 1800 km (± 51° look angles) from 803-km altitude

Pointing Requirements (3σ):

Control: <0.3° (~1000 arcsec)

Knowledge: <0.05° (~167 arcsec)

Stability: <0.008°/s (30 arcsec/s)

Contributor: NASA JPL designed

forecasting. SeaWinds was a follow-on to the NASA Scatterometer (NSCAT) on ADEOS; the SeaWinds instrument on ADEOS II complemented an identical instrument on the QuikSCAT spacecraft.

The SeaWinds scatterometer used a 1-m-diameter dish antenna with two beams, which rotated about the satellite nadir axis at 18 rpm. SeaWinds radiated and received microwave pulses at a frequency of 13.4 GHz across an 1800-km-wide swath.

Scatterometers use a highly indirect technique to measure wind velocity over the ocean. Changes in the wind velocity cause changes in ocean surface roughness, modifying the radar cross section of the ocean and the magnitude of the backscattered power. Multiple collocated measurements acquired from several viewing geometries (incidence angles, polarizations, and directions) are used to determine wind speed and direction simultaneously. The directly measured backscatter cross-sections over land and ice-covered regions yield information on vegetation type and ice type and extent.

A full write-up on the SeaWinds instruments is found under the entry for QuikSCAT, which carries a SeaWinds instrument identical to the one that was on ADEOS II.

SeaWinds URL

winds.jpl.nasa.gov/

SeaWinds Principal Investigator

Michael Freilich, Oregon State University

ADEOS II References

Freilich, M. H., and R. S. Dunbar, 1999: The accuracy of the NSCAT 1 vector winds: comparisons with National Data Buoy Center buoys. *J. Geophys. Res.*, **104**, 11,231–11,246.

Liu, W. T., ed., 2003: Scientific Opportunities Provided by SeaWinds in Tandem. JPL Publication 03-12, Jet Propulsion Laboratory, Pasadena, 39 pp.

Liu, W. T., 2002: Progress in scatterometer application. *J. Oceanogr.*, **58**, 121–136.

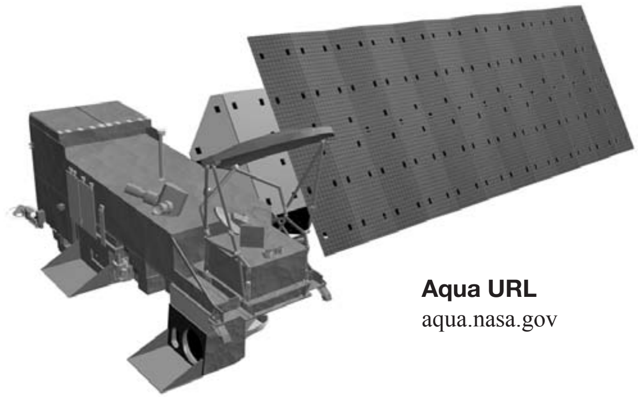
Note: Additional SeaWinds references are provided in the QuikSCAT section.

ADEOS II Data Products

Product Name or Grouping	Processing Level	Coverage	Spatial/Temporal Characteristics
SeaWinds *Data Set Start Date: April 10, 2003; Data Set End Date: October 24, 2003*			
Normalized Radar Cross Section and Ancillary Data	1B	Global	6 × 25-km horizontal resolution, 70% daily and 90% every 2 days
Grouped and Surface-Flagged Backscatter and Attenuations	2A	Global	25 × 25-km horizontal resolution, 70% daily and 90% every 2 days
Ocean Wind Vectors in 25-km Grid	2B	Oceans	25-km horizontal resolution, 90% every 2 days
Ocean Wind Vectors on regular lat-lon grid	3	Oceans	25-km horizontal resolution, 90% every 2 days
Note: Since SeaWinds is the only EOS instrument that flew on ADEOS II, only its data-product information is included here.			

ADEOS II Data Products

Aqua



Aqua URL
aqua.nasa.gov

Key Aqua Facts

Joint with Brazil and Japan

Orbit:
Type: Near polar, sun-synchronous
Altitude: 705 km
Equatorial Crossings: 1:30 p.m. (south to north) and 1:30 a.m. (north to south)
Inclination: 98.2°
Period: 98.8 minutes
Repeat Cycle: 16 days (233 revolutions)

Dimensions: 2.7 m × 2.5 m × 6.5 m stowed; 4.8 m × 16.7 m × 8.0 m deployed

Mass: 2,934 kg (1,750 kg spacecraft, 1,082 kg instruments, 102 kg propellants)

Power: 4,600 W silicon cell array and a NiH_2 battery

Design Life: 6 years

Average Data Rate: 89 Gbytes/day

Data Storage: 136-Gbit solid state recorder (SSR) for storage of up to two orbits of data

Data Relay Methods: Direct downlink from the SSR to polar ground stations; direct broadcast

Data Links: X-band

Telemetry: S-band

Summary

Aqua is a major international Earth Science satellite mission centered at NASA. Launched on May 4, 2002, the satellite has six different Earth-observing instruments on board and is named for the large amount of information being obtained about water in the Earth system from its stream of approximately 89 Gigabytes of data a day. The water variables being measured include almost all elements of the water cycle and involve water in its liquid, solid, and vapor forms. Additional variables being measured include radiative energy fluxes, aerosols, vegetation cover on the land, phytoplankton and dissolved organic matter in the oceans, and air, land, and water temperatures.

Instruments

- Atmospheric Infrared Sounder (AIRS)
- Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E)
- Advanced Microwave Sounding Unit – A (AMSU-A)
- Clouds and the Earth's Radiant Energy System (CERES; two copies)
- Humidity Sounder for Brazil (HSB)
- Moderate Resolution Imaging Spectroradiometer (MODIS)

Points of Contact

- *Aqua Project Scientist:* Claire Parkinson, NASA Goddard Space Flight Center
- *Aqua Deputy Project Scientist:* Steven Platnick, NASA Goddard Space Flight Center

Other Key Personnel

- *Aqua Program Scientist:* Ramesh Kakar, NASA Headquarters
- *Aqua Program Executive:* Lou Schuster, NASA Headquarters
- *Aqua Mission Director:* William Guit, NASA Goddard Space Flight Center

Mission Type

Earth Observing System (EOS) Systematic Measurements

Launch

- *Date and Location:* May 4, 2002, from Vandenberg Air Force Base, California
- *Vehicle:* Delta II 7920-10L rocket, with a 10-ft diameter stretched fairing

Relevant Science Focus Areas
(see NASA's Earth Science Program section)

- Atmospheric Composition
- Carbon Cycle, Ecosystems and Biogeochemistry
- Climate Variability and Change
- Water and Energy Cycles
- Weather

Related Applications
(see Applied Sciences Program section)

- Agricultural Efficiency
- Air Quality
- Carbon Management
- Coastal Management
- Disaster Management
- Ecological Forecasting
- Homeland Security
- Water Management

Aqua Science Goals

- Enhanced understanding of water in the Earth's climate system and the global water cycle.
- Enhanced understanding of additional components of the Earth's climate system and their interactions.
- Improved weather forecasting.

Aqua Mission Background

The Aqua spacecraft takes its name from 'Aqua,' Latin for 'water,' in recognition of the large amount of data the Aqua instruments are collecting about the Earth's water and its water cycle. This includes data about ocean surface water, evaporation from the oceans, water vapor in the atmosphere, clouds, precipitation, soil moisture, sea ice, land ice, and snow cover on the land and ice. Additional variables also being measured by Aqua include radiative energy fluxes, atmospheric aerosols, vegetation cover on the land, phytoplankton and dissolved organic matter in the oceans, and air, land, and water temperatures.

Through its wide-ranging global measurements, the Aqua mission is assisting scientists in better quantifying the state of the highly interconnected Earth system and in addressing such key topics as whether the water cycle is accelerating, whether the Earth system is in radiative balance, and what the full role of clouds is in the climate system. Many of the topics of interest to Aqua scientists and others concern regional and global changes, with the most frequently highlighted one being global warming but others including Arctic sea ice decay, stratospheric ozone reductions, atmospheric carbon dioxide increases, tropical and mid-latitude deforestation, and degradation of water quality. All of these topics are being examined by Aqua scientists, but most of these variables have interannual variability that can overwhelm long-term trends. Hence an important aspect of maximizing the use of the Aqua data is linking it to earlier satellite data sets, even though some of those

Aqua Instruments

AIRS
Atmospheric Infrared Sounder

A high spectral resolution grating spectrometer containing 2378 infrared channels for obtaining atmospheric temperature profiles and a variety of additional Earth/atmosphere products. AIRS also has 4 visible/near-infrared channels, for characterizing cloud and surface properties and obtaining higher spatial resolution than the infrared measurements.

AMSR-E (Japan)
Advanced Microwave Scanning Radiometer for the Earth Observing System

A 12-channel microwave radiometer designed to monitor a broad range of hydrologic variables, including precipitation, cloud water, water vapor, sea surface winds, sea surface temperature, sea ice, snow, and soil moisture.

AMSU-A
Advanced Microwave Sounding Unit-A

A 15-channel microwave sounder designed to obtain temperature profiles in the upper atmosphere and to provide a cloud-filtering capability for the AIRS infrared measurements, for increased accuracy in tropospheric temperature profiles.

CERES
Clouds and the Earth's Radiant Energy System

A 3-channel, broadband radiometer (0.3 to > 100 μm, 0.3–5 μm, 8–12 μm) designed to measure major elements of the Earth's radiation budget.

HSB (Brazil)
Humidity Sounder for Brazil

A 4-channel microwave sounder designed to obtain humidity profiles under cloudy conditions and detect heavy precipitation.

MODIS
Moderate Resolution Imaging Spectroradiometer

A 36-band spectroradiometer measuring visible and infrared radiation, for derivation of products ranging from land vegetation and ocean chlorophyll fluorescence to cloud and aerosol properties, fire occurrence, snow cover on land, and sea ice in the oceans.

data sets might be of lesser quality. For instance, the Aqua radiation-budget data are being linked with earlier satellite Earth radiation-budget data going back to the early 1980s, the Aqua vegetation data are being linked with earlier satellite vegetation indices also going back to the early 1980s, and the Aqua sea ice data are being linked with satellite sea ice records going back to the 1970s.

To make its measurements, the Aqua spacecraft carries six Earth observing instruments: the AIRS, AMSU-A, HSB, AMSR-E, CERES, and MODIS, all described in more detail on the following pages. The AIRS, AMSU-A, and HSB are sounders, obtaining information at many levels in the atmosphere, while the AMSR-E, CERES, and MODIS are imagers. The AIRS, CERES, and MODIS measure in visible and infrared wavelengths, while the AMSR-E, AMSU-A, and HSB measure in microwave wavelengths. The combination greatly enhances the range of applications of the data, with, for instance, the microwave data enabling surface observations under all lighting conditions and most weather conditions and the visible data enabling detailed cloud studies as well as greater spatial detail in the surface and atmospheric measurements.

Prior to launch, five Aqua science teams developed algorithms to convert the radiative data from each of the six instruments into meaningful geophysical parameters. After launch, each of these teams has been enhanced with new members and has analyzed the Aqua data, refined the algorithms, and carried out validation activities. The five teams are:

- The AIRS/AMSU-A/HSB Science Team (generally abbreviated as the AIRS Science Team), covering the full Aqua sounding suite. This team is centered at NASA's Jet Propulsion Laboratory and is led by Moustafa Chahine.

- The Japanese AMSR-E Science Team, centered in Japan and led by Akira Shibata.

- The U.S. AMSR-E Science Team, centered at NASA Marshall Space Flight Center and the University of Alabama and led by Roy Spencer.

- The CERES Science Team, centered at NASA Langley Research Center and led by Bruce Wielicki.

- The MODIS Science Team, centered at NASA Goddard Space Flight Center and led by Vince Salomonson.

Aqua data are transmitted from the spacecraft through two processes: direct downlink and direct broadcast. The direct downlink transmits the data from an on-board solid state recorder (SSR) to polar ground stations in Alaska and Svalbard, Norway. Direct downlink is routinely done each orbit, although the SSR has the capacity to hold up to two orbits of data. When direct downlink is not taking place, the direct broadcast system is generally in operation, allowing anyone with a direct broadcast receiver to receive the raw Aqua data.

From the polar ground stations, the downlinked data are transmitted to Goddard Space Flight Center, where the data processing is done for the MODIS, AIRS, AMSU-A, and HSB data. The CERES data are sent to Langley Research Center for processing, and the AMSR-E data are sent to Japan's Earth Observation Center (EOC) for initial processing, followed by further processing at Remote Sensing Systems and at Marshall Space Flight Center. After processing, the Aqua data and the derived products are made available through several NASA Distributed Active Archive Centers (DAACs). In particular: the AMSR-E data and the MODIS snow and ice products are available from the National Snow and Ice Data Center (NSIDC) DAAC; the AIRS/AMSU-A/HSB data and the MODIS ocean and atmosphere products are available from the NASA Goddard Space Flight Center DAAC; the CERES data are available from the NASA Langley Research Center DAAC; and the MODIS land products are available from the Earth Resources Observation System (EROS) Data Center DAAC.

The Aqua data are proving useful in several direct applications as well as for scientific advances. Most notably, the MODIS data on forest fires have been valuable in fire fighting efforts, the MODIS data on dust have been valuable in observing and tracking dust storms in Iraq and its vicinity, and AIRS/AMSU-A, MODIS, CERES, and AMSR-E data are all proving potentially useful in weather forecasting.

Aqua Partners

Aqua is a joint project involving many countries, with the primary ones being the United States, Japan, and Brazil. The spacecraft and the AIRS, AMSU-A, CERES, and MODIS instruments were all provided by the U.S., as was the launch vehicle, while the AMSR-E instrument was provided by Japan, and the HSB instrument was provided by Brazil. More specifically, NASA Goddard Space Flight Center provided the MODIS and AMSU-A instruments; NASA's Jet Propulsion Laboratory provided the AIRS instrument; NASA Langley Research Center provided the two CERES instruments; the National Space Development Agency of Japan (NASDA) provided the AMSR-E instrument; and Brazil's Instituto Nacional de Pesquisas Espaciais (INPE, the Brazilian Institute for Space Research) provided the HSB instrument. Subsequent to the delivery of the AMSR-E, NASDA was merged into the new Japan Aerospace Exploration Agency (JAXA) on October 1, 2003.

TRW (now Northrop Grumman) constructed and tested both the spacecraft and the two CERES instruments. AIRS was built by BAE Systems, AMSR-E by Mitsubishi Electronics, AMSU-A by Aerojet, HSB by Matra-Marconi, and MODIS by Raytheon Santa Barbara Remote Sensing. TRW contracted out the construction of Aqua's solar array, which was built in the Netherlands by Fokker. Boeing built the Delta launch vehicle, while NASA Kennedy Space Center was responsible for the launch operations and the U.S. Air Force was responsible for all range-related matters at the Vandenberg launch site.

Overall management of the Aqua mission is centered at NASA Goddard Space Flight Center. This included management of the integration and testing of the spacecraft prior to launch and continues to include operation of the spacecraft and initial receipt, processing, and dissemination of the data. Further processing of the data takes place within the individual science teams and at the following NASA DAACs: NSIDC in Boulder, Colorado; the NASA Goddard Space Flight Center DAAC in Greenbelt, Maryland; the NASA Langley Research Center DAAC in Hampton, Virginia; and the EROS Data Center DAAC in Sioux Falls, South Dakota.

Many additional countries, universities, and agencies are also involved in the Aqua mission through science team membership and validation activities. The Aqua science teams include scientists from Japan, Brazil, Australia, Belgium, Canada, France, Italy, Nigeria, Saudi Arabia, South Africa, and the United Kingdom, as well as from the U.S. Validation activities are taking place at ocean and land sites around the globe.

AIRS/AMSU-A/HSB

- **Atmospheric Infrared Sounder (AIRS)**
- **Advanced Microwave Sounding Unit (AMSU-A)**
- **Humidity Sounder for Brazil (HSB)**

Summary

AIRS, the Atmospheric Infrared Sounder, and two operational microwave sounders, AMSU-A and HSB, form the AIRS (or AIRS/AMSU-A/HSB) sounding system. AIRS, AMSU-A, and HSB measurements are analyzed jointly to filter out the effects of clouds from the infrared data, in order to derive clear-column air temperature profiles with high vertical resolution and accuracy, as well as high accuracy surface temperatures. Together, these instruments constitute an advanced sounding system, surpassing the Television and Infrared Observation Satellite (TIROS) Operational Vertical Sounder (TOVS)/Advanced TOVS (ATOVS) systems that currently operate on NOAA satellites, and serve as a pathfinder to the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Cross-track Infrared Sounder (CrIS).

The data retrieved from the AIRS/AMSU-A/HSB instrument suite improve global circulation modeling efforts, numerical weather prediction, the study of the global energy and water cycles, detection of the effects of greenhouse gases, investigation of atmosphere-surface interactions, and monitoring of climate variations and trends. These objectives are met through improvements in the accuracy, stability, and yield of several weather and climate parameters, including atmospheric temperature and water vapor, land and ocean surface temperature, cloud properties, and outgoing longwave radiation. The AIRS/AMSU-A/HSB data are being used by scientists around the world to better understand weather and climate and by the U.S. National Weather Service and other forecasting agencies from around the world to improve weather prediction.

AIRS Data Products

AIRS, AMSU-A, and HSB together constitute a single facility instrument program, so data products labeled as "AIRS Products" are often the result of calculations involving AMSU-A and/or HSB data as well as AIRS data. The HSB ceased operating in February 2003. The data products provided from the AIRS, AMSU-A, and HSB measurements are:

Level 1B Products

Level 1B products include the calibrated and geolocated radiances from the AIRS, AMSU-A, and HSB. The AIRS Level 1B products are presented in separate files for the infrared AIRS data and the visible/near-infrared AIRS data.

Level 2 Products

The Level 2 standard core products for AIRS, AMSU-A, and HSB include cloud-cleared infrared radiances, sea and land surface temperatures, temperature and humidity profiles, total precipitable water, fractional cloud cover, cloud top height, and cloud top temperature. All Level 2 products are contained in three files: the Level 2 Standard Retrieval Product, Level 2 Cloud-Cleared Radiance, and Level 2 Support Product. The Level 2 Support Product includes research products under development for which the feasibility, achievable accuracy, precision, and spatial and temporal coverage are not fully established. Research products include total-column carbon dioxide, total-column carbon monoxide, methane distribution, ozone vertical distribution, other trace gases (SO_2, etc.), surface air temperature, spectrally resolved outgoing radiation, a precipitation index, and cirrus cloud detection and characterization. A validation report accompanies each released version of the AIRS products, describing the extent and the level to which the products have been characterized.

Root-Mean-Square Uncertainties in AIRS, AMSU-A, and HSB Radiance and Standard Products

Radiance Products (Level 1B)	**RMS Uncertainty***
AIRS Infrared Radiance	0.1–0.5 K
AIRS Visible/Near-Infrared Radiance	20%
AMSU-A Radiance	0.25–1.2 K
HSB Radiance	1.0–1.2 K
Standard Core Products (Level 2)	**RMS Uncertainty***
Cloud-Cleared IR Radiance	1.0 K
Sea Surface Temperature	0.5 K
Land Surface Temperature	1.0 K
Temperature Profile (vertical resolution: 1 km below 700 Mb, 2 km 700–30 Mb)	1 K
Humidity Profile (vertical resolution: 2 km in troposphere)	15%
Total Precipitable Water	5%
Fractional Cloud Cover	5%
Cloud Top Height	0.5 km
Cloud Top Temperature	1.0 K

* Radiance error defined as the temperature error of a Planck blackbody at 250 K. The nominal horizontal resolution of the AIRS infrared and HSB radiance products is 15 km × 15 km, AIRS visible/near-infrared products 2.5 km × 2.5 km, and the remaining products 45 km × 45 km.

Level 3 Products

AIRS Level 3 products are composed of Level 2 geophysical data that have been spatially and/or temporally re-sampled to a uniform spatial grid. Level 3 data sets are substantially smaller than the lower level source products from which they are derived due to resampling and selecting a reduced set of reporting parameters. Level 3 products provide a global view of AIRS data in a record size that

Key AIRS Facts

Launch: May 4, 2002 on Aqua

Heritage: Advanced Moisture and Temperature Sounder (AMTS), High Resolution Infrared Radiation Sounder (HIRS)

Instrument Type: Temperature controlled (155 K) array grating spectrometer, plus a visible/near-infrared photometer

Aperture: 10 cm

Channels:
Infrared: 2378
Visible/near-infrared: 4

Spectral Range:
Infrared: 3.74–15.4 µm (3.74–4.61, 6.2–8.22, 8.8–15.4 µm);
Visible/near-infrared: 0.4–1.0 µm (0.4–0.44, 0.58–0.68, 0.71–0.92, 0.49–0.94 µm)

Spectral Resolution: $\lambda/\Delta\lambda$ 1200 nominal

Swath Width: 1650 km

Coverage: Global coverage every 1 to 2 days

Spatial Resolution:
Infared: 13.5 km at nadir
Visible/near-infrared: 2.3 km at nadir

Dimensions: 116.5 cm × 80 cm × 95.3 cm

Mass: 177 kg

Thermal Control:
Infrared detectors: 58 K by active cooling (pulse tube cryocoolers)

Spectrometer: 156 K by two-stage passive radiator, heater

Electronics: ~290 K by spacecraft heat rejection system

Blackbody: 308 K by heater

Power: 180/220 W (beginning/end of life)

Duty Cycle: 100%

Data Rate: 1.27 Mbps

Field of View (FOV): ± 49.5° cross-track from nadir

Instrument IFOV (track/scan):
Infrared: 1.1° × 0.6° (13.5 km × 7.4 km at nadir);
Visible/near-infrared: 0.149° × 0.190° (1.8 km × 2.3 km at nadir)

Calibration: Internal blackbody, space, parylene (spectral) views; 3 visible/near-infrared lamps

Pointing Accuracy: Infrared: 0.1° (2σ)

is manageable for long term or large scale studies. The uniform spatial gridding of the Level 3 products allows comparisons of data sets from different sources. AIRS Level 3 product development is driven by the need for global analysis of AIRS data for weather and climate studies and for an easy-to-use, quantitative gridded data set for interdisciplinary studies. A partial list of Level 3 products includes temperature and water vapor profiles, surface skin temperature, surface air temperature, column ozone, and column liquid water.

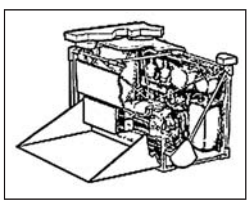
Product Validation

The Level 2 retrieval initially delivered to the GSFC DAAC (version 3.0.8.0 in August 2003) met AIRS Project requirements for nighttime, ocean fields of view within the latitude band 40°S – 40°N. Subsequent deliveries (approximately annually) include the activation and/or improvement of the validation status of subsets of the products, plus validation over a greater geographical and temporal extent. Phased activations are planned to expand the latitude range to include all non-polar nighttime ocean regions, non-polar daytime ocean retrievals, non-polar nighttime land retrievals, followed by non-polar daytime land retrievals. The final step will be to activate the polar retrievals.

AIRS

Atmospheric Infrared Sounder (AIRS)

Simultaneously measures the Earth's outgoing radiation in 2378 infrared channels from 3.7 to 15.4 µm and four visible/near-infrared channels from 0.4 to 1 µm. Used to obtain high resolution temperature and humidity profiles within the atmosphere, plus a variety of additional Earth/atmosphere products.



AIRS is designed to meet the NOAA requirement of a high-resolution infrared (IR) sounder to fly on future operational weather satellites.

The core of the AIRS instrument is a high-resolution infrared sounder, measuring simultaneously in 2378 spectral channels in the 3.74–15.4 µm spectral range. The spectral resolution ($\lambda/\Delta\lambda$) is nominally 1200. The high spectral resolution enables the separation of the contribution of unwanted spectral emissions and, in particular, provides radiometrically clear "super windows," ideal for surface observations. AIRS also provides four visible/near-infrared channels (0.4–1.0 µm) to characterize cloud and surface properties. The data from all channels are downlinked on a routine operational basis.

Temperature profiles from AIRS are derived even in the presence of multiple cloud layers, without requiring any field-of-view to be completely clear. Humidity profiles are derived from channels in the 6.3 µm water vapor band and the 11 µm windows, which are sensitive to the water vapor continuum. Determination of the surface temperature and surface spectral emissivity is essential for obtaining low-level water vapor distributions.

Key AIRS Facts *(cont.)*

Scan Period: 2.667 s

Scan Sampling (scan/track): Infrared: 90 × 1 (1.1° spacing), in 2 s; visible/near-infrared: 720 × 9 (0.138° × 0.185° spacing), in 2 s

Sensitivity (NEΔT): 0.09–0.45 K, depending on spectral region

Design Life: 5 years

Direct Broadcast: Yes

Prime Contractor: BAE SYSTEMS (formerly Lockheed-Martin)

Responsible Center: NASA Jet Propulsion Laboratory

Land skin surface temperature and the corresponding infrared emissivity are determined simultaneously with the retrieval of the atmospheric temperature and water profiles. Shortwave window channels are used to derive the surface temperature and corresponding spectral emissivity and to account for reflected solar radiation. Once the surface temperature is determined, the longwave surface emissivity for the 11 µm region is determined and then is used to retrieve the water vapor distribution near the surface.

Cloud-top heights and effective cloud amount are determined based on the calculated atmospheric temperature, humidity, and surface temperature, combined with the calculated clear-column radiance and measured radiance. The spectral dependence of the opacity of the clouds will distinguish various cloud types (including cirrus clouds). Ozone retrieval is performed simultaneously with the retrievals of the other parameters, using the 9.6 µm ozone band.

AIRS visible and near-IR channels between 0.4 and 1.0 µm are used primarily to discriminate between low-level clouds and different terrain and surface covers, including snow and ice. In addition, the visible channels allow the determination of cloud, land, and ocean surface parameters simultaneously with atmospheric corrections. One broadband channel from 0.4 to 1.0 µm is used for the estimation of reflected shortwave radiation, i.e., albedo. The other three channels are used for surface properties such as ice and snow amount and vegetation index.

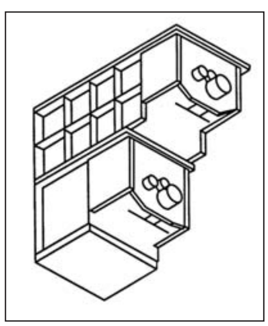
AIRS URL

airs.jpl.nasa.gov/

AMSU-A1 and AMSU-A2

Advanced Microwave Sounding Unit (AMSU-A)

Provides atmospheric temperature measurements from the surface up to 40 km. Onboard NOAA 15/16/17/18 as well as Aqua.



AMSU-A is a 15-channel microwave sounder that obtains temperature profiles in the upper atmosphere and provides a cloud-filtering capability for the AIRS infrared channels for increased accuracy of tropospheric temperature observations. The fifteen AMSU-A channels have a 3.3° beam width, resulting in a nominal horizontal spatial resolution of 40.5 km at nadir.

Channels 3 to 14 on AMSU-A are situated on the low-frequency side of the oxygen resonance band (50–60 GHz) and are used for temperature sounding. Successive channels in this band are situated at frequencies with increasing opacity and therefore respond to radiation from increasing altitudes. Channel 1, located on the first (weak) water vapor resonance line, is used to obtain estimates of total column water vapor in the atmosphere. Channel 2 (at 31 GHz) is used to indicate the presence of rain. Channel 15 on AMSU-A,

Key AMSU-A Facts

Launches: May 13, 1998 on NOAA 15; September 21, 2000 on NOAA 16; May 4, 2002 on Aqua; May 21, 2002 on NOAA 17; May 20, 2005 on NOAA 18

Heritage: Microwave Sounding Unit (MSU)

Instrument Type: Microwave radiometer

Aperture: 13.2 cm on AMSU-A1 (two apertures); 27.4 cm on AMSU-A2 (one aperture)

Channels: 15 (13 for AMSU-A1, 2 for AMSU-A2)

Spectral Range: 23–90 GHz (50–90 GHz for AMSU-A1, 23–32 GHz for AMSU-A2)

Swath Width: 1690 km

Coverage: Global coverage every 1–2 days

Spatial Resolution: 40.5 km at nadir

Dimensions: 72 cm × 34 cm × 59 cm for AMSU-A1; 73 cm × 61 cm × 86 cm for AMSU-A2

Mass: 91 kg (49 kg for AMSU-A1, 42 kg for AMSU-A2)

Thermal Control: None (ambient)

Power: 101 W (77 W for AMSU-A1, 24 W for AMSU-A2)

Duty Cycle: 100%

Data Rate: 2.0 kbps (1.5 kbps for AMSU-A1, 0.5 kbps for AMSU-A2)

FOV: ± 49.5° cross-track from nadir

Instrument IFOV: 3.3° (40.5 km at nadir) for both units

Calibration: Internal blackbody, space view

Pointing Accuracy: 0.2°

Scan Period: 8 s

Scan Sampling: 30 × 3.3°, in 6 s

Sensitivity: 0.14–0.81 K, depending on spectral region

Design Life: 3 years

Direct Broadcast: Yes

Prime Contractor: Northrop Grumman (formerly Aerojet)

Responsible Center: NASA Goddard Space Flight Center at 89 GHz, is used as an indicator for precipitation, using the fact that at 89 GHz ice more strongly scatters radiation than it absorbs or emits radiation.

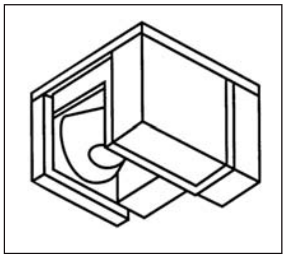
AMSU-A URL

airs.jpl.nasa.gov/

HSB

Humidity Sounder for Brazil

Provided atmospheric water vapor profile measurements until February 2003. (HSB has been non-operational since February 2003 due to an apparent electrical component failure in the scan drive system. Periodic attempts have been made to restart it.)



HSB is a 4-channel microwave sounder designed to obtain atmospheric humidity profiles under cloudy conditions and to detect heavy precipitation under clouds. The four HSB channels have a 1.1° beam width, resulting in a nominal horizontal spatial resolution of 13.5 km.

Three of the HSB channels make measurements on the wings of the strongly opaque water vapor resonance line at 183.3 GHz; the fourth makes measurements at 150 GHz. Successive channels have decreasing opacity and consequently their data correspond to humidities at decreasing altitudes. The four HSB channels improve the humidity profiles from AIRS/AMSU-A in the presence of liquid water.

AIRS/AMSU/HSB Science Team Leader

Moustafa Chahine, NASA Jet Propulsion Laboratory/California Institute of Technology

Key HSB Facts

Launch: May 4, 2002 on Aqua

Heritage: AMSU-B

Instrument Type: Microwave radiometer

Aperture: 18.8 cm

Channels: 4

Spectral Range: 150–190 GHz

Swath Width: 1650 km

Coverage: Global every 1 to 2 days

Spatial Resolution: 13.5 km at nadir

Dimensions: 70 cm × 65 cm × 46 cm

Mass: 51 kg

Thermal Control: None (ambient)

Power: 56 W

Duty Cycle: 100%

Data Rate: 4.2 kbps

FOV: ± 49.5° cross-track from nadir

Instrument IFOV: 1.1° (13.5 km at nadir)

Calibration: Internal blackbody, space view

Pointing Accuracy: 0.1°

Scan Period: 2.667 s

Scan Sampling: 90 × 1.1°, in 1.71 s

Sensitivity: 0.3–0.68 K, depending on spectral region

Design Life: 3 years

Direct Broadcast: Yes, until February 2003

Prime Contractor: Astrium (formerly Matra Marconi Space, United Kingdom)

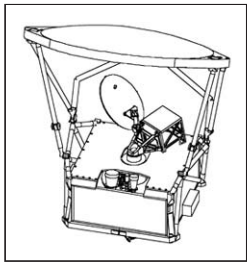
Provider: Instituto Nacional de Pesquisas Espaciais (INPE, the Brazilian Institute for Space Research)

AMSR-E

Advanced Microwave Scanning Radiometer-EOS

Provides daily, global all-weather measurements of geophysical parameters, supporting several global change science and monitoring efforts. (One day's data cover most of the globe; the full globe is covered within two days.)

Summary



AMSR-E monitors various atmospheric and surface water processes that influence weather and climate. It provides improved measurements of rain rates and greatly extends the spatial coverage of the Tropical Rainfall Measuring Mission (TRMM) satellite, while also measuring water vapor, sea surface winds, sea surface temperature, sea ice, soil moisture, snow cover, and the amount of water in clouds.

Background

The Aqua AMSR-E measures geophysical parameters supporting several global change science and monitoring efforts. Of particular importance to its success is an external calibration design, which has proved suitable in other satellite microwave instrumentation for long-term monitoring of subtle changes in temperature and other variables.

Precipitation and evaporation have extremely important roles in the Earth system, through provision of water to the biosphere via precipitation and as an air conditioning agent that removes excess heat from the surface (via evaporation), thereby contributing toward making Earth habitable. AMSR-E measurements are used to calculate rain rates over both land and ocean. Over the ocean, radiation at the AMSR-E microwave frequencies passes through smaller cloud particles, allowing measurement of the microwave emission from the larger raindrops. The AMSR-E provides sensitivity to oceanic rain rates as high as 50 mm/hr (about 2 inches per hour). Over land, AMSR-E measures the scattering effects of large ice particles, which later melt to form raindrops. These measurements, though less direct a measure of rainfall intensity, are converted to rain rates with the help of cloud models.

Over the ocean, in addition to rain rates, AMSR-E provides sea surface temperatures (SST) through most types of cloud cover, supplementing infrared-based measurements of SST that are restricted to cloud-free areas. SST fluctuations are known to have a profound impact on weather patterns across the globe, and AMSR-E's all-weather capability could provide a significant improvement in our ability to monitor SSTs and the processes controlling them.

The total integrated water vapor of the atmosphere is also measured over the ocean. This variable is important for the understanding of how water is cycled through the atmosphere. Since water vapor is the Earth's primary greenhouse gas, and it contributes the most to future projections of global warming, it is critical to understand how it varies naturally in the Earth system.

Key AMSR-E Facts

Launch: May 4, 2002 on Aqua (a similar instrument, AMSR, was launched on December 14, 2002 on ADEOS II)

Heritage: SMMR (on Nimbus-7 and Seasat), SSM/I (on DMSP), AMSR (on ADEOS II)

Instrument type: Passive microwave radiometer, twelve channels, six frequencies, dual polarization (vertical and horizontal); offset parabolic reflector, 1.6 m in diameter and drum rotating at 40 rpm; six feedhorns to cover six bands from 6.9–89 GHz with 0.3–1.1 K radiometric sensitivity.

Channels: 12

Spectral Range: 0.34–4.35 cm

Frequency Range: 6.9–89.0 GHz

Swath Width: 1445 km

Coverage: Global coverage every 1 to 2 days

Spatial Resolution: 6 km × 4 km (89.0 GHz), 14 km × 8 km (36.5 GHz), 32 km × 18 km (23.8 GHz), 27 km × 16 km (18.7 GHz), 51 km × 29 km (10.65 GHz), 74 km × 43 km (6.925 GHz)

Dimensions:
Sensor Unit: 1.95 m × 1.7 m × 2.4 m (deployed)
Control Unit: 0.8 m × 1.0 m × 0.6 m

Mass: 314 kg

Thermal Control: Passive radiator, thermostatically controlled heaters

Thermal Operating Range: -5° – 40°C (receiver qualification temperature)

Power: 350 W

Duty Cycle: 100%

Data Rate: 87.4 kbps average, 125 kbps peak

View: Forward-looking conical scan

Incidence Angle: 55°

Instrument IFOV at Nadir: Ranges from 74 km × 43 km for 6.9 GHz to 6 km × 4 km for 89.0 GHz

Sampling Interval: 10 km for 6–36 GHz channel

Calibration: External cold load reflector and a warm load for calibration

Accuracy: 1 K or better

Design Life: 3 years

Direct Broadcast: Yes

Prime Contractor: Mitsubishi Electric Company (MELCO)

Responsible Agency: Originally the National Space Development Agency of Japan (NASDA); as of October 1, 2003, the Japan Aerospace Exploration Agency (JAXA)

Measurements by AMSR-E of ocean surface roughness can be converted into estimated near-surface wind speeds. These winds are an important determinant of how much water is evaporated from the surface of the ocean. The winds help to maintain the water vapor content of the atmosphere, while precipitation continually removes it.

AMSR-E cloud-water estimates over the ocean help determine whether clouds, with their ability to reflect sunlight, increase or decrease under various conditions. This could be an important feedback mechanism that either enhances or mitigates global warming, depending on whether clouds increase or decrease with warming.

Monitoring of sea ice parameters, such as ice concentration and extent, is necessary to understand how this frozen blanket over the ocean affects the larger climate system. In winter, sea ice insulates the water against heat loss to the frigid atmosphere above it, whereas in summer sea ice reflects sunlight that would otherwise warm the ocean. AMSR-E measurements allow the derivation of sea ice concentrations in both polar regions, through taking advantage of the marked contrast in microwave emissions of sea ice and liquid water.

In much the same way as AMSR-E can 'see' large ice particles in the upper reaches of rain systems, it also measures the scattering effects of snow cover. These measurements are empirically related to snow-cover depth and water content based upon field measurements. Like sea ice, snow cover has a large influence on how much sunlight is reflected from the Earth. It also acts as a blanket, keeping heat from escaping from the underlying soil and allowing deep cold air masses to develop during the winter. It further provides an important storage mechanism for water during the winter months, and this affects how much surface wetness is available for vegetation and crops in the spring. AMSR-E monitoring of snow cover allows studies on how snow-cover variations interplay with other climate fluctuations.

Wet soil can be identified in the AMSR-E observations if not too much vegetation is present. AMSR-E provides the most useful satellite data yet for determination of how well low-frequency (6.9 and 10.65 GHz) microwave observations can be used to monitor surface wetness. Surface wetness is important for maintaining crop and vegetation health, and its monitoring on a global basis would allow drought-prone areas to be checked for signs of ongoing drought.

AMSR-E URLs

sharaku.eorc.jaxa.jp/AMSR/index_e.htm

wwwghcc.msfc.nasa.gov/AMSR/

AMSR-E Science Teams

There are two science teams involved in the production of AMSR-E (and AMSR) products for the science community: a U.S. AMSR-E team organized by NASA, and a Japan AMSR/AMSR-E team organized by the Japan Aerospace Exploration Agency (JAXA). Members from each team constitute a Joint AMSR Team that works together to share findings and unify procedures for analysis of the data. Both teams are also involved in field campaigns to help validate the products. AMSR flew on ADEOS II, launched on December 14, 2002, and operated until October 2003.

U.S. AMSR-E Science Team Leader

Roy W. Spencer, University of Alabama in Huntsville

Japan AMSR-E Science Team Leader

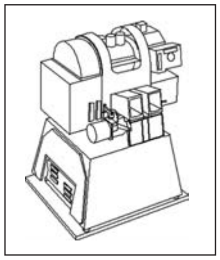
Akira Shibata, Earth Observation Research Center, JAXA

CERES

Clouds and the Earth's Radiant Energy System

Provides daily, global measurements in three broad radiation bands for details on the Earth's radiation budget.

Summary



CERES is a 3-channel radiometer aimed at collecting information about the Earth's radiative balance. Two CERES instruments are onboard Aqua and two are onboard Terra. For each satellite, one CERES instrument (while cross-track scanning) essentially continues the Earth Radiation Budget Experiment (ERBE) mission, while the second instrument (bi-axially scanning, in rotating azimuth plane scan mode) provides angular radiance information that will improve the accuracy of angular models used to derive the Earth's radiative balance. Each of the CERES instruments can operate in either of the two scanning modes.

Background

The CERES instruments provide accurate radiation flux measurements from the surface to the top of the atmosphere (TOA) that are fundamental inputs to models of oceanic and atmospheric energetics and that will also contribute to extended-range weather forecasting. These data have been requested for the Climate Change Science Program and for international efforts of the World Climate Research Program (WCRP), including the Tropical Ocean Global Atmosphere (TOGA) campaign, World Ocean Circulation Experiment (WOCE), Global Energy and Water Cycle Experiment (GEWEX), Global Climate Observing System (GCOS), and Indian Ocean Experiment (INDOEX). Understanding the role of clouds and radiation in the climate system is one of the highest priorities of the U.S. Global Change Research Program.

Clouds are regarded by many scientists as the largest source of uncertainty in understanding climate. Not only are clouds highly variable and difficult to measure, but they have competing heating and cooling effects on the Earth-atmosphere system. Clouds cool the Earth by reflecting part of the large flow of incoming radiative energy from the Sun but warm the Earth by enhancing the atmospheric greenhouse effect. CERES measures the radiative flows at the top of the atmosphere (TOA), and CERES scientists combine these data with data from higher resolution imagers (VIRS on TRMM, MODIS on Terra and Aqua) to calculate cloud properties and radiative fluxes through the atmosphere as well as the radiative energy budget at the Earth's surface. The imagers allow determination of cloud top height, fractional area, cloud liquid water path, droplet size, and other cloud properties that are consistent with the radiative fluxes. CERES is providing, for the first time, a critical tie between the measurements of the radiation budget and synchronous measurements of cloud properties. This capability is expected to be critical to uncovering cause and effect in cloud/climate feedback mechanisms.

Key CERES Facts

Launches: November 27, 1997 on the Tropical Rainfall Measuring Mission (TRMM; one CERES); December 18, 1999 on Terra (two CERES); and May 4, 2002 on Aqua (two CERES). A follow-on instrument will fly on NPOESS.

Heritage: ERBE

Instrument Type: Each CERES is a broadband, scanning radiometer capable of operating in either of two modes: cross-track or rotating plane (bi-axial scanning). On each of Aqua and Terra, typically one CERES operates in one mode and the second CERES operates in the other mode. The scan azimuth can be programmed for special science studies or validation operations.

Channels: 3 in each radiometer

Spectral Range: One channel each measuring total radiance (0.3 to >100 µm), shortwave radiance (0.3–5 µm), and the radiance in the atmospheric window at 8–12 µm

Swath Width: Limb to limb of the Earth view from each satellite

Coverage: Global coverage daily

Spatial Resolution: 10 km at nadir for TRMM, 20 km at nadir for Terra and Aqua

Dimensions: 60 cm × 60 cm × 57.6 cm/unit (stowed), 60 cm × 60 cm × 70 cm/unit (deployed)

Mass: 50 kg per scanner

Thermal Control: Heaters, radiators

Thermal Operating Range: 37–39°C (detectors)

Power: 47 W (average), 68 W (peak: biaxial mode) per scanner

Duty Cycle: 100%

Data Rate: 10 kbps per scanner

FOV: ±78° cross-track, 360° azimuth

Instrument IFOV: 14 mrad

Direct Broadcast: Yes (on Aqua)

Prime Contractor: NGST

Responsible Center: NASA Langley Research Center

The CERES instruments use a scanner very similar to the ERBE scanner to determine TOA fluxes. Key developments in meeting the CERES goal to double the accuracy of existing estimates of radiative fluxes include new models of the anisotropy of the Earth's reflected and emitted radiation (using the CERES bi-axial scanner) as well as improved time-sampling methods merging CERES data with high time resolution geostationary satellite data. CERES is also providing improved measurements of clear-sky radiative fluxes. Improvements in clear-sky fluxes require near-simultaneous measurements of both well-calibrated cloud-imager and broadband radiation measurements. Highly accurate clear-sky radiative fluxes are critical in assessing the land/ocean heat budget, as well as understanding the role of aerosols and clouds in the climate system.

Finally, the CERES Team produces Level 3 data products derived by time interpolation and integration of the Level 2 data into monthly averages. The time interpolation process is aided by data from geostationary imagers. Thus, CERES scientists are determining the structure of the atmospheric energy budget over the life of the CERES missions, with a time resolution of three hours in the synoptic data product. For long-term climate understanding, the CERES Team also produces data products that contain monthly averages of the cloud and radiation fields on a uniform spatial grid. During combined Terra, Aqua, and TRMM observations, the Level 3 CERES data products merge information from 11 instruments on 7 spacecraft.

CERES URLs

asd-www.larc.nasa.gov/ceres/ASDceres.html
(CERES Home Page, including CERES brochure, documentation, meetings, and links to activities)

eospso.gsfc.nasa.gov/eos_homepage/for_scientists/publications.php *(EOS Data Products Handbook, including CERES data product descriptions)*

asd-www.larc.nasa.gov/ATBD/ATBD.html
[CERES Algorithm Theoretical Basis Documents (ATBDs)]

asd-www.larc.nasa.gov/validation/valid_doc.html
(CERES Validation Plan)

CERES Principal Investigator

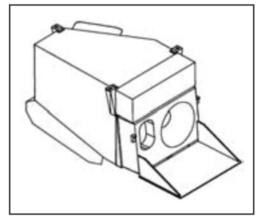
Bruce Wielicki, NASA Langley Research Center

MODIS

Moderate Resolution Imaging Spectroradiometer

Provides daily, global observations of biological and physical parameters on and near land and ocean surfaces and in the atmosphere. (One day's data cover most of the globe; the full globe is covered within two days.)

Summary



MODIS is a multi-disciplinary, keystone instrument on Aqua and Terra, providing a wide array of multispectral, daily observations of land, ocean, and atmosphere features at spatial resolutions between 250 m and 1000 m. Approximately 40 data products are produced from the MODIS data. Data are distributed not only through the EOS Data and Information Service (EOSDIS) Distributed Active Archive Centers (DAACs) at Goddard Space Flight Center, the EROS Data Center in Sioux Falls, South Dakota, and the National Snow and Ice Data Center (NSIDC) in Boulder, Colorado, but also via over 100 Direct Broadcast (DB) stations distributed world-wide.

Background

MODIS is an EOS facility instrument designed to measure biological and physical processes on a global basis every 1 to 2 days. Onboard both the Terra and Aqua satellites, the two multidisciplinary MODIS instruments are providing long-term observations from which an enhanced knowledge of global dynamics and processes occurring on the surface of the Earth and in the lower atmosphere can be derived. Each MODIS instrument is supplying simultaneous, congruent observations of high-priority atmospheric features (aerosol properties, cloud cover, cloud optical thickness, cloud phase, cloud top pressure, temperature and water vapor profiles), oceanic features (sea surface temperature, ocean color and related ocean surface water constituents such as chlorophyll concentration), and land-surface features (land-cover changes, atmospherically-corrected land surface reflectance, land-surface temperature, surface albedo, fire location and intensity, snow cover, and vegetation properties). These observations are expected to make major contributions to understanding the global Earth system, including interactions among land, ocean, and atmospheric processes.

The MODIS instrument employs a conventional imaging spectroradiometer concept, consisting of a cross-track scan mirror and collecting optics, and a set of linear arrays with spectral interference filters located in four focal planes. The optical arrangement provides imagery in 36 discrete bands between 0.4 and 14.5 µm selected for diagnostic significance in Earth science. The spectral bands have spatial resolutions of 250, 500, or 1,000 m at nadir. Signal-to-noise ratios are greater than 500 at 1-km resolution (at a solar zenith angle of 70°), and absolute irradiance accuracies are < ±5% from 0.4 to 3 µm (2% relative to the Sun) and 1% or better in the thermal infrared wavelengths (3.7–14.5 µm). MODIS provides daylight reflection and day/night emission spectral imaging of any point on the Earth at least every 2 days, operating continuously.

MODIS is included on both the Terra and Aqua satellites to increase cloud-free remote sensing of the Earth's surface and to exploit synergism with other EOS sensors.

MODIS URLs

modis.gsfc.nasa.gov/ *(general instrument status and related overall Science Team matters)*

modis-land.gsfc.nasa.gov *(MODIS land information)*

edcdaac.usgs.gov/dataproducts.asp *(MODIS land products)*

nsidc.org/daac/modis/index.html *(MODIS cryosphere products)*

modis-atmos.gsfc.nasa.gov *(MODIS atmosphere information)*

ladsweb.nascom.nasa.gov/MODIS/products.shtml *(MODIS Level 1 data, geolocation, cloud mask, and atmosphere products)*

oceancolor.gsfc.nasa.gov *(MODIS ocean color and sea surface temperature products)*

www.mcst.ssai.biz/mcstweb/index.html *(calibration and characterization details for the MODIS instrument and Level 1 product characteristics)*

modis.gsfc.nasa.gov/data/ and modis.gsfc.nasa.gov/data/dataprod/index.php *(MODIS data products, overview)*

MODIS Science Team Leader

Vincent V. Salomonson, University of Utah and NASA Goddard Space Flight Center, *emeritus*.

Key MODIS Facts

Launches: December 18, 1999 on Terra; May 4, 2002 on Aqua

Heritage: AVHRR, HIRS, Landsat TM, and Nimbus-7 CZCS

Instrument Type: Medium-resolution, multi-spectral, cross-track scanning radiometer; daylight reflection and day/night emission spectral imaging

Channels: 36 spectral bands

Spectral Range: 20 bands within 0.4–3.0 µm; 16 bands within 3–14.5 µm

Swath Width: 2,300 km at 110° (± 55°)

Coverage: Global coverage every 1 to 2 days

Spatial Resolution: 250 m, 500 m, 1 km

Dimensions: 1.04 m × 1.18 m × 1.63 m

Mass: 229 kg

Thermal Control: Passive radiators

Thermal Operating Range: 268 ± 5 K

Power: 162.5 W (average), 225 W (peak)

Duty Cycle: 100%

Data Rate: 6.2 Mbps (average), 10.5 Mbps (daytime), 3.2 Mbps (nighttime)

Instrument Nadir IFOV: 250 m (2 bands), 500 m (5 bands), 1,000 m (29 bands)

Polarization Sensitivity: 2% from 0.43 µm to 2.2 µm and ± 45° scan

Signal-to-Noise Ratios: From 500 to 1100 for 1-km ocean color bands at 70° solar zenith angle

NE∆t: Typically < 0.05 K at 300 K

Absolute Irradiance Accuracy: 5% for wavelengths < 3 µm and 1% for wavelengths > 3 µm

Direct Broadcast: Yes

Prime Contractor: Raytheon Santa Barbara Remote Sensing

Responsible Center: NASA Goddard Space Flight Center

Aqua References

AIRS/AMSU-A/HSB References

Aumann, H. H., M. T. Chahine, S. Lee, and E. T. Olsen, 2003: Results from the Atmospheric Infrared Sounder (AIRS) on the EOS Aqua. *Proc. 30th International Symposium on Remote Sensing of the Environment*, Honolulu, Hawaii, November 10–14.

Aumann, H. H., M. T. Chahine, and D. Barron, 2003: Sea surface temperature measurements with AIRS: RTG.SST comparison. *Proc. SPIE Earth Observing Systems VIII*, San Diego, California, **5151**, 252–261.

Aumann, H. H., M. T. Chahine, C. Gautier, M. D. Goldberg, E. Kalnay, L. M. McMillin, H. Revercomb, P. W. Rosenkranz, W. L. Smith, D. H. Staelin, L. L. Strow, and J. Susskind, 2003: AIRS/AMSU/HSB on the Aqua mission: Design, science objectives, data products, and processing systems. *IEEE Trans. Geosci. Remote Sens.*, **41 (2)**, 253–264.

Chen, F. W., and D. H. Staelin, 2003: AIRS/AMSU/HSB precipitation estimates. *IEEE Trans. Geosci. Remote Sens.*, **41 (2)**, 410–417.

Fetzer, E., E. T. Olsen, and L. L. Chen, 2003: Validation of AIRS/AMSU/HSB retrieved products. *Proc. SPIE Earth Observing Systems VIII*, San Diego, California, **5151**, 211–219.

Gaiser, S. L., H. H. Aumann, D. T. Gregorich, and T. J. Hearty, 2003: In-flight refinement of the radiometric, spectral, and spatial calibration of the Atmospheric Infrared Sounder (AIRS). *Proc. SPIE Earth Observing Systems VIII*, San Diego, California, **5151**, 232–243.

Gaiser, S. L., H. H. Aumann, L. L. Strow, S. E. Hannon, and M. Weiler, 2003: In-flight spectral calibration of the Atmospheric Infrared Sounder. *IEEE Trans. Geosci. Remote Sens.*, **41 (2)**, 287–297.

Gautier, C., Y. Shiren, and M. D. Hofstadter, 2003: AIRS/Vis near IR instrument. *IEEE Trans. Geosci. Remote Sens.*, **41 (2)**, 330–342.

Goldberg, M. D., Y. Qu, L. M. McMillin, W. Wolf, L. Zhou, and M. Divakarla, 2003: AIRS near-real-time products and algorithms in support of operational numerical weather prediction. *IEEE Trans. Geosci. Remote Sens.*, **41 (2)**, 379–389.

Lambrigtsen, B. H., 2003: Calibration of the AIRS microwave instruments. *IEEE Trans. Geosci. Remote Sens.*, **41 (2)**, 369–378.

Lambrigtsen, B. H., and S.-Y. Lee, 2003: Co-alignment and synchronization of the AIRS instrument suite. *IEEE Trans. Geosci. Remote Sens.*, **41 (2)**, 343–351.

Pagano, T. S., H. H. Aumann, D. E. Hagan, and K. Overoye, 2003: Prelaunch and in-flight radiometric calibration of the Atmospheric Infrared Sounder (AIRS). *IEEE Trans. Geosci. Remote Sens.*, **41 (2)**, 265–273.

Pagano, T. S., M. T. Chahine, H. H. Aumann, D. A. Elliott, E. M. Manning, V. J. Realmoto, C. K. Thompson, B. H. Lambrigtsen, S.-Y. Lee, S. E. Broberg, E. T. Olsen, E. J. Fetzer, and L. L. Strow, 2003: AIRS/AMSU/HSB on EOS Aqua: First year post launch assessment. *Proc. SPIE Earth Observing Systems VIII*, San Diego, California, **5151**, 201–210.

Rosenkranz, P. W., 2001: Retrieval of temperature and moisture profiles from AMSU-A and AMSU-B measurements. *IEEE Trans. Geosci. Remote Sens.*, **39**, 2429–2435.

Rosenkranz, P. W., 2003: Rapid radiative transfer model for AMSU/HSB channels. *IEEE Trans. Geosci. Remote Sens.*, **41 (2)**, 362–368.

Strow, L. L., S. E. Hannon, S. De Souza-Machado, H. E. Motteler, and D. Tobin, 2003: An overview of the AIRS radiative transfer model. *IEEE Trans. Geosci. Remote Sens.*, **41 (2)**, 303–313.

Strow, L. L., S. E. Hannon, S. De Souza-Machado, and H. E. Motteler, 2003: Validation of the AIRS radiative transfer algorithm using ECMWF data fields. *Proc. SPIE Remote Sensing of the Clouds and Atmosphere VII*, Crete, Greece, **4882**, 90–99.

Susskind, J., C. Barnet, J. Blaisdell, L. Iredell, F. Keita, and L. Kouvaris, 2003: Early results from AIRS/AMSU/HSB. *Proc. SPIE Earth Observing Systems VIII*, San Diego, California, **5151**, 244–251.

Susskind, J., C. D. Barnet, and J. M. Blaisdell, 2003: Retrieval of atmospheric and surface parameters from AIRS/AMSU/HSB data in the presence of clouds. *IEEE Trans. Geosci. Remote Sens.*, **41 (2)**, 390–409.

AMSR-E References

Chang, A., R. Kelly, J. Foster, and D. Hall, 2003: Estimation of global snow cover using passive microwave data. *Proc. SPIE*, **4894**, 381–390.

Chen, C., L. Tsang, J. Guo, A. Chang, and K. Ding, 2003: Frequency dependence of scattering and extinction of dense media based on three-dimensional simulations of Maxwell's equations with applications to snow. *IEEE Trans. Geosci. Remote Sens.*, **41**, 1844–1852.

Comiso, J. C., D. J. Cavalieri, and T. Markus, 2003: Sea ice concentration, ice temperature, and snow depth using AMSR-E data. *IEEE Trans. Geosci. Remote Sens.*, **41 (2)**, 243–252.

Kawanishi, T., T. Sezai, Y. Ito, K. Imaoka, T. Takeshima, Y. Ishido, A. Shibata, M. Miura, H. Inahata, and R. W. Spencer, 2003: The Advanced Microwave Scanning Radiometer for the Earth Observing System (AMSR-E), NASDA's contribution to the EOS for global energy and water cycle studies. *IEEE Trans. Geosci. Remote Sens.*, **41 (2)**, 184–194.

Kelly, R. E., A. T. Chang, L. Tsang, and J. L. Foster, 2003: A prototype AMSR-E global snow area and snow depth algorithm. *IEEE Trans. Geosci. Remote Sens.*, **41 (2)**, 230–242.

Markus, T., and D. J. Cavalieri, 2000: An enhancement of the NASA Team sea ice algorithm. *IEEE Trans. Geosci. Remote Sens.*, **38**, 1387–1398.

Njoku, E., and L. Li, 1999: Retrieval of land surface parameters using passive microwave measurements at 6 to 18 GHz. *IEEE Trans. Geosci. Remote Sens.*, **37**, 79–93.

Njoku, E. G., T. J. Jackson, V. Lakshmi, T. K. Chan, and S. V. Nghiem, 2003: Soil moisture retrieval from AMSR-E. *IEEE Trans. Geosci. Remote Sens.*, **41 (2)**, 215–229.

Shibata, A., K. Imaoka, and T. Koike, 2003: AMSR/AMSR-E Level 2 and 3 algorithm developments and data validation plans of NASDA. *IEEE Trans. Geosci. Remote Sens.*, **41 (2)**, 195–203.

Wentz, F. J., and M. Schabel, 2000: Precise climate monitoring using complementary satellite data sets. *Nature*, **403 (6768)**, 414–416.

Wentz, F. J., C. Gentemann, D. Smith, and D. B. Chelton, 2000: Satellite measurements of sea surface temperature through clouds. *Science*, **288 (5467)**, 847–850.

Wentz, F. J., C. Gentemann, and P. Ashcroft, 2003: On-orbit calibration of AMSR-E and the retrieval of ocean products. *AMS 12th Conference on Satellite Meteorology and Oceanography*, in Long Beach, California.

Wilheit, T., C. D. Kummerow, and R. Ferraro, 2003: Rainfall algorithms for AMSR-E. *IEEE Trans. Geosci. Remote Sens.*, **41 (2)**, 204–214.

Aqua References

Parkinson, C. L., 2003: Aqua: An Earth-observing satellite mission to examine water and other climate variables. *IEEE Trans. Geosci. Remote Sens.*, **41 (2)**, 173–183.

Parkinson, C. L., and R. Greenstone, eds., 2000: *EOS Data Products Handbook, Volume 2: ACRIMSAT, Aqua, Jason-1, Landsat 7, Meteor-3M/SAGE III, QuikScat, QuikTOMS, and VCL*, NASA Goddard Space Flight Center, Greenbelt, Maryland, 253 pp.

Parkinson, C. L., M. T. Chahine, C. D. Kummerow, and V. V. Salomonson, 2003: Foreword to the EOS Aqua Special Issue. *IEEE Trans. Geosci. Remote Sens.*, **41 (2)**, 172.

CERES References

Charlock, T. P., and T. L. Alberta, 1996: The CERES/ARM/GEWEX Experiment (CAGEX) for the retrieval of radiative fluxes with satellite data. *Bull. Amer. Meteor. Soc.*, **77**, 2673–2683.

Loeb, N. G., N. Manalo-Smith, S. Kato, W. F. Miller, S. K. Gupta, P. Minnis, and B. A. Wielicki, 2003: Angular distribution models for TOA radiative flux estimation from CERES instrument on the TRMM satellite. Part I: Methodology. *J. Appl. Meteor.*, **42**, 240–265.

Priestley, K. J., B. A. Wielicki, R. N. Green, M. P. A. Haeffelin, R. B. Lee, and N. G. Loeb, 2002: Early radiometric validation results of the CERES Flight Model 1 and 2 instruments onboard NASA's Terra spacecraft. *Adv. Space Res.*, **30**, 2371–2376.

Wielicki, B. A., R. D. Cess, M. D. King, D. A. Randall, and E. F. Harrison, 1995: Mission to Planet Earth: Role of clouds and radiation in climate. *Bull. Amer. Meteor. Soc.*, **76**, 2125–2153.

Wielicki, B. A., B. R. Barkstrom, E. F. Harrison, R. B. Lee III, G. L. Smith, and J. E. Cooper, 1996: Clouds and the Earth's Radiant Energy System (CERES): An Earth Observing System experiment. *Bull. Amer. Meteor. Soc.*, **77**, 853–868.

Wielicki, B. A., B. R. Barkstrom, B. A. Baum, T. P. Charlock, R. N. Green, D. P. Kratz, R. B. Lee III, P. Minnis, G. L. Smith, T. Wong, D. F. Young, R. D. Cess, J. A. Coakley Jr., D. A. H. Crommelynck, L. Donner, R. Kandel, M. D. King, A. J. Miller, V. Ramanathan, D. A. Randall, L. L. Stowe, and R. M. Welch, 1998: Clouds and the Earth's Radiant Energy System (CERES): Algorithm overview. *IEEE Trans. Geosci. Remote Sens.*, **36**, 1127–1141.

Young, D. F., P. Minnis, D. R. Doelling, G. G. Gibson, and T. Wong, 1998: Temporal interpolation methods for the CERES experiment. *J. Appl. Meteor.*, **37**, 572–590.

MODIS References

Barnes W. L., X. Xiong, and V. V. Salomonson, 2003: Status of Terra MODIS and Aqua MODIS. *Adv. Space Res.*, **32 (11)**, 2099–2106.

Baum, B. A., and S. Platnick, 2005: Introduction to MODIS cloud products, in J. J. Qu, W. Gao, M. Kafatos, R. E. Murphy, and V. V. Salomonson, eds., *Earth Science Satellite Remote Sensing: Volume 1, Science and Instruments*, Springer-Verlag and Tsinghua University Press, in press.

Carder, K. L., J. P. Cannizzaro, F. R. Chen, S. W. Bailey, and J. P. Werdell, 2004: Toward a climate quality chlorophyll dataset: Global validation of a semi-analytical chlorophyll a algorithm. For Ocean Optics XVII, Fremantle, Australia, October 28, 2004, CDROM, Office of Naval Research, Arlington, Virginia, 6 p.

Esaias, W., M. Abbott, O. Brown, J. Campbell, K. Carder, D. Clark, R. Evans, F. Hoge, H. Gordon, W. Balch, R. Letelier, and P. Minnett, 1998: An overview of MODIS capabilities for ocean science observations. *IEEE Trans. Geosci. Remote Sens.*, **36**, 1250–1265.

Guenther, B., X. Xiong, V. V. Salomonson, W. L. Barnes, and J. Young, 2002: On-orbit performance of the Earth Observing System Moderate Resolution Imaging Spectroradiometer; first year of data. *Remote Sens. Environ.*, **83 (1)**, 16–30.

Jin, M., J. M. Shepherd, and M. D. King, 2005: Urban aerosols and their variations with clouds and rainfall: A case study for New York and Houston. *J. Geophys. Res.*, **110**, D10S20, doi:10.1029/2004JD005081.

Justice, C. O., J. R. G. Townshend, E. F. Vermote, E. Masuoka, R. E. Wolfe, N. Saleous, D. P. Roy, and J. T. Morisette, 2002: An overview of MODIS land data processing and product status. *Remote Sens. Environ.*, **83 (1)**, 3–15.

King, M. D., W. P. Menzel, Y. J. Kaufman, D. Tanré, B.-C. Gao, S. Platnick, S. A. Ackerman, L. A. Remer, R. Pincus, and P. A. Hubanks, 2003: Cloud and aerosol properties, precipitable water, and profiles of temperature and water vapor from MODIS. *IEEE Trans. Geosci. Remote Sens.*, **41 (2)**, 442–458.

Minnett, P.J., O. B. Brown, R. H. Evans, E. L. Key, E. J. Kearns, K. Kilpatrick, A. Kumar, K. A. Maillet, and G. Szczodrak, 2004: Sea-surface temperature measurements from the Moderate-Resolution Imaging Spectroradiometer (MODIS) on Aqua and Terra. *Proceedings of the IEEE International Geosciences and Remote Sensing Symposium*, Anchorage, Alaska, September 20–24, 2004, volume 7, 4576–4579.

Platnick, S., M. D. King, S. A. Ackerman, W. P. Menzel, B. A. Baum, J. C. Riédi, and R. A. Frey, 2003: The MODIS cloud products: Algorithms and examples from Terra. *IEEE Trans. Geosci. Remote Sens.*, **41 (2)**, 459–473.

Remer, L. A., Y. J. Kaufman, D. Tanre, S. Mattoo, D. A. Chu, J. V. Martins, R-R. Li, C. Ichoku, R. C. Levy, R. G. Kleidman, T. F. Eck, E. Vermote, and B. N. Holben, 2005: The MODIS aerosol algorithm, products and validation. *J. Atmos. Sci.*, **62**, 947–973.

Roy, D. P., Y. Jin, P. E. Lewis, and C. O. Justice, 2005: Prototyping a global algorithm for systematic fire-affected area mapping using MODIS time series data. *Remote Sens. Environ.*, **97**, 137–162.

Salomonson, V. V., W. Barnes, and E. J. Masuoka, 2005: An introduction to MODIS and an overview of associated activities, in J. J. Qu, W. Gao, M. Kafatos, R. E. Murphy, and V. V. Salomonson, eds., *Earth Science Satellite Remote Sensing: Volume 1, Science and Instruments*, Springer-Verlag and Tsinghua University Press, in press.

Xiong, X. X., and W. Barnes, 2006: An overview of MODIS radiometric calibration and characterization. *Advances Atmos. Sci.*, **23 (1)**, 69–79.

Aqua Data Products

Data from the six Aqua instruments are used to produce dozens of data products on different aspects of the Earth's water cycle. The pre-launch descriptions of these products are given in the *EOS Data Products Handbook*, Volume 2 (Parkinson and Greenstone, 2000), which can be found at: eos.nasa.gov/eos_homepage/for_scientists/data_products. The various data products are at different levels of maturity and validation, but the table here provides a brief overview. Additional information can be found in the individual instrument sections. Future updates regarding data products and data availability should be available through the URLs provided in the instrument sections.

Product Name or Grouping	Processing Level	Coverage	Spatial/Temporal Characteristics
AIRS/AMSU-A/HSB *Data Set Start Date: August 31, 2002; End Date for the HSB Data: February 5, 2003*			
Level 1B Calibrated, Geolocated Radiances	1B	Global	AIRS infrared (IR): 13.5 km resolution at nadir/twice daily (daytime and nighttime) AIRS visible/near-infrared (Vis): 2.3 km resolution at nadir/twice daily AMSU-A: 40.5 km resolution at nadir/twice daily HSB: 13.5 km resolution at nadir/twice daily
Cloud Cleared Radiances	2	Global	40.5 km resolution at nadir/twice daily
Flux Product (clear column radiance, outgoing longwave and shortwave radiation at the top of the atmosphere, net longwave and shortwave flux)	2	Global	40.5 km resolution at nadir/twice daily
Atmospheric Temperature Product (temperature profile)	2	Global	40.5 km at nadir; 28 vertical levels (1-km levels below 700 mb and 2-km levels between 700 and 30 mb)/ twice daily (daytime and nighttime)
Humidity Product (water vapor profile in 2 km layers in the troposphere, total precipitable water, cloud liquid water content, precipitation flag, cloud-ice flag)	2	Global	40.5 km resolution at nadir/twice daily
Cloud Product (cloud top pressure and temperature, spectral properties, cloud fraction and variability index)	2	Global	40.5 km at nadir for cloud top pressure and temperature, spectral properties; 13.5 km at nadir for cloud fraction and variability index/once or twice daily (varies with parameter)
Ozone Product (ozone concentration profile and total)	2	Global	40.5 km resolution at nadir/twice daily (daytime and nighttime)
Trace Constituent Product (CO, CH_4, CO_2)	2	Global	40.5 km resolution at nadir/twice daily
Surface Analysis Product (sea and land surface skin temperature, infrared and microwave surface emissivity)	2	Global	40.5 km resolution at nadir/twice daily
Level 3 Products (temperature and water vapor profiles, surface skin temperature, surface air temperature, column ozone, and column liquid water)	3	Global	1° × 1° grid cells/1-day, 8-day, and monthly averages

Aqua Data Products

Product Name or Grouping	Processing Level	Coverage	Spatial/Temporal Characteristics
AMSR-E *Data Set Start Date: June 18, 2002*			
Columnar Cloud Water	2, 3	Global ocean surface, clear and cloudy skies and light rainfall	Level 2: swath pixels at 12 km resolution Level 3: 0.25° latitude-longitude grid/daily, weekly, and monthly
Columnar Water Vapor	2, 3	Global ocean surface, clear and cloudy skies and up-to-moderate rainfall rates	Level 2: swath pixels at 21-km resolution Level 3: 0.25° latitude-longitude grid/daily, weekly, and monthly
Level 2A Brightness Temperature	2A	Global	Swath pixels at resolutions from 5 to 56 km
Rainfall – Level 2	2	70° N – 70° S ice-free and snow-free land and ocean	Satellite orbit track, 5-km resolution
Rainfall – Level 3	3	70° N – 70° S	5° × 5°/monthly
Sea Ice Concentration	3	Global	12.5 and 25 km/ascending, descending, and daily averages
Sea Ice Temperature	3	Global	25 km/ascending, descending, and daily averages
Sea Surface Temperature	2, 3	Global ocean surface, clear and cloudy skies except in the presence of rainfall	Level 2: swath pixels at 38-km and 56-km resolution Level 3: 0.25° latitude-longitude grid/daily, weekly, and monthly
Sea Surface Wind Speed	2, 3	Ocean surface, clear and cloudy skies except in the presence of rainfall	Level 2: swath pixels at 24-km and 38-km resolution Level 3: 0.25° latitude-longitude grid/daily, weekly, and monthly
Snow Depth on Sea Ice	3	Southern Ocean and the Arctic seasonal sea ice zones	12.5 km/5-day average
Snow Water Equivalent and Snow Depth	3	Global land surface	EASE grid 25-km resolution/daily, 5-day, monthly
Surface Soil Moisture	2, 3	Global land surface, although only under snow-free and low-vegetation conditions	56-km spatial resolution on a nominal 25-km Earth-fixed grid; swath (Level 2) and daily (Level 3) ascending and descending
Note: The AMSR-E data products are being archived at the National Snow and Ice Data Center (NSIDC) in Boulder, Colorado, where the corresponding products for the Japanese AMSR instrument on Midori II (formerly ADEOS II) will also be archived, for the seven months of Midori II operations, December 2002–October 2003.			

Aqua Data Products

Product Name or Grouping	Processing Level	Coverage	Spatial/Temporal Characteristics
CERES *Data Set Start Date: June 18, 2002*			
Bi-Directional Scans Product	0, 1	Global	20 km at nadir/0.01 second
ERBE-like Instantaneous TOA Estimates	2	Global	20 km at nadir/0.01 second
ERBE-like Monthly Regional Averages (ES-9) and ERBE-like Monthly Geographical Averages (ES-4)	3	Global	2.5°, 5.0°, 10.0°, region and zone, global/monthly (by day and hour)
Single Scanner TOA/Surface Fluxes and Clouds	2	Global	20 km at nadir/0.01 second
Clouds and Radiative Swath	2	Global	20 km at nadir/0.01 second
Monthly Gridded Radiative Fluxes and Clouds	3	Global	1° region/hourly
Synoptic Radiative Fluxes and Clouds	3	Global	1° region/3-hour, monthly
Average (AVG) (used for the CERES Monthly Regional Radiative Fluxes and Clouds data product); Zonal Average (ZAVG) (used for the CERES Monthly Zonal and Global Radiative Fluxes and Clouds data product)	3	Global	1° region, 1° zone, global/monthly
Monthly Gridded TOA/Surface Fluxes and Clouds	3	Global	1° region/hourly
Monthly TOA/Surface Averages	3	Global	1° region/monthly
MODIS *Data Set Start Date: June 25, 2002*			
Level 1B Calibrated, Geolocated Radiances	1B	Global	0.25, 0.5, and 1 km/daily (daytime and nighttime)
Geolocation Data Set	1B	Global	1 km /daily (daytime and nighttime)
Aerosol Product	2	Global over oceans, nearly global over land	10 km/daily daytime
Total Precipitable Water	2	Global	Varies with retrieval technique; 1 km near-infrared/daylight only, and 5 km infrared/day and night
Cloud Product	2	Global	1 or 5 km/once or twice per day (varies with parameter)
Atmospheric Profiles	2	Global, clear-sky only	5 km/daily (daytime and nighttime)

Aqua Data Products

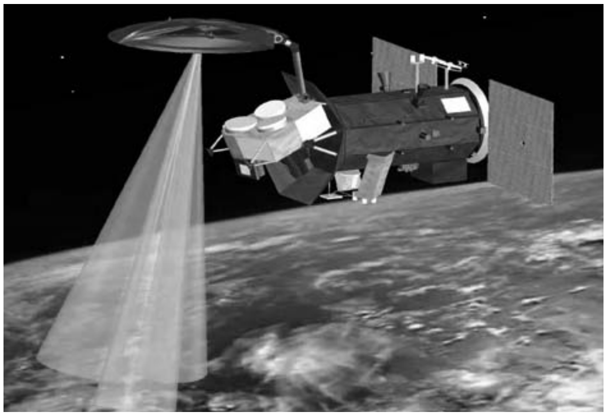
Product Name or Grouping	Processing Level	Coverage	Spatial/Temporal Characteristics
MODIS			
Atmosphere Level 2 Joint Product (select subset)	2	Global	5 or 10 km/once or twice per day (varies with parameter)
Atmosphere Level 3 Joint Product	3	Global	1.0° latitude-longitude equal-angle grid/daily, 8-day, and monthly
Cloud Mask	2	Global	250 m and 1 km/daily
Surface Reflectance; Atmospheric Correction Algorithm Products	2	Global land surface	500 m, 0.05°, and 0.25°/daily
Snow Cover	2, 3	Global, daytime	500 m and 0.05°/daily; 500 m and 0.05°/8-day; 0.05°/monthly
Land Surface Temperature (LST) and Emissivity	2, 3	Global land surface	1 km, 5 km/daily; 1 km/8-day
Land Cover/Land Cover Dynamics	3	Global, clear-sky only	1 km and 0.05°/yearly
Vegetation Indices	3	Global land surface	250 m, 500 m, 1 km/16-day; 1 km/monthly
BRDF/Albedo	3	Global land surface	1 km, 0.05°/16-day
Land Cover Change and Conversion	3, 4	Global, daytime	250 m, 500 m/96-day, yearly
Thermal Anomalies/Fire	2, 3	Global, daytime/ nighttime	Swath (nominally 1-km) (Level 2); 1 km/daily, 8-day (Level 3)
Leaf Area Index (LAI) and Fraction of Photosynthetically Active Radiation (FPAR)	4	Global	1 km/8-day
Net Photosynthesis and Net Primary Production	4	Global	1 km/8-day, yearly
Normalized Water-Leaving Radiance (412, 443, 488, 531, 551, and 667 nm)	2, 3	Global ocean surface, clear-sky only	1 km/daily (Level 2); 4 km, 9 km/daily, 8-day, monthly, seasonal, yearly (Level 3)
Chlorophyll *a* Concentration	2, 3	Global ocean surface, clear-sky only	1 km/daily (Level 2); 4 km, 9 km/daily, 8-day, monthly, seasonal, yearly (Level 3)
Ocean Diffuse Attenuation Coefficient at 490 nm	2, 3	Global ocean surface, clear-sky only	1 km/daily (Level 2); 4 km, 9 km/daily, 8-day, monthly, seasonal, yearly (Level 3)
Sea Surface Temperature (11 μm, day and night; 4 μm, night)	2, 3	Global ocean surface, clear-sky only	1 km/daily (Level 2); 4 km, 9 km/daily, 8-day, monthly, yearly (Level 3)

Aqua Data Products

Product Name or Grouping	Processing Level	Coverage	Spatial/Temporal Characteristics
MODIS			
Sea Ice Cover and Ice-Surface Temperature	2, 3	Global, daytime and nighttime over nonequatorial ocean	1 km, 0.05°/daily
Epsilon of Aerosol Correction at 748 and 869 nm	2, 3	Global ocean surface, clear-sky only	1 km/daily (Level 2); 4 km, 36 km, 1°/daily, 8-day, monthly, yearly (Level 3)
Aerosol Optical Thickness (869 nm)	2, 3	Global ocean surface, clear-sky only	1 km/daily (Level 2); 4 km, 9 km/daily, 8-day, monthly, seasonal, yearly (Level 3)
Ångstrom Coefficient (531–869 nm)	2, 3	Global ocean surface, clear-sky only	1 km/daily (Level 2); 4 km, 9 km/daily, 8-day, monthly, seasonal, yearly (Level 3)

Aqua Data Products

Aquarius



Aquarius URL
aquarius.gsfc.nasa.gov

Summary

Aquarius is a joint U.S. (NASA)/Argentine (Comisión Nacional de Actividades Espaciales [CONAE]) venture. The mission will enhance the understanding of the climatic interactions between the global water cycle and ocean circulation by systematically mapping the spatial and temporal variations of sea surface salinity (SSS). It will measure SSS variability, the key tracer for freshwater input and output to the ocean associated with precipitation, evaporation, ice melting, and river runoff. These measurements, along with sea surface temperature (SST) from other satellites, will allow determination of the sea surface density, which controls the formation of water masses and regulates the 3-dimensional ocean circulation.

Instrument

• Aquarius Instrument

Note: Aquarius is part of the Aquarius/Satelite de Aplicaciones Cientificas (SAC)-D mission in partnership with the Argentine space agency CONAE. The CONAE SAC-D payload includes other scientific instruments not described in detail in this document. The SAC-D mission is described in detail at: www.conae.gov.ar/eng/satelites/sac-d.html.

Points of Contact

- *Aquarius Principal Investigator:* Gary Lagerloef, Earth & Space Research (ESR)
- *Aquarius Deputy Principal Investigator:* David Le Vine, NASA Goddard Space Flight Center

Key Aquarius Facts

Joint with Argentina

Orbit:
- Type: Sun-synchronous
- Equatorial Crossing (ascending node): 6 a.m.
- Altitude: 657 km
- Inclination: 98.01°
- Period: 97.74 minutes
- Repeat Cycle: 7 days (103 orbits)

Dimensions: 4.9 m (ht) × 2.7 m (diameter), stowed; 6.2 m (ht) × 2.7 m (diameter), deployed

Mass: 1515 kg

Power: 1300 W End of Life

Downlink: S-band @ 4 kbps for real time housekeeping; X-band @ >13.5 mbps for stored and real time science data.

Design Life: 3 years

Contributors: CONAE, NASA JPL, NASA GSFC

Other Key Personnel

- *Aquarius Project Scientist:* Yi Chao, NASA Jet Propulsion Laboratory/California Institute of Technology
- *Aquarius Project Manager:* Amit Sen, NASA Jet Propulsion Laboratory/California Institute of Technology
- *Aquarius Deputy Project Manager:* Yunjin Kim, NASA Jet Propulsion Laboratory/California Institute of Technology
- *Aquarius Program Scientist:* Eric Lindstrom, NASA Headquarters
- *Aquarius Program Executive:* Eric Ianson, NASA Headquarters
- *SAC-D Principal Investigator:* F. Raul Colomb, CONAE
- *SAC-D Project Manager:* C. Daniel Caruso, CONAE

Mission Type

Next Generation Exploratory Mission (Earth System Science Pathfinder)

Launch

- *Date and Location:* No earlier than 2009, from Vandenberg Air Force Base, California
- *Vehicle:* Delta II 7320-10C

Relevant Science Focus Areas

(see NASA's Earth Science Program section)

- Climate Variability and Change
- Water and Energy Cycles

Related Applications

(see Applied Sciences Program section)

- Agricultural Efficiency
- Water Management

Note: Applications listed regard coarse soil moisture measurements that can be derived using Aquarius.

Aquarius Science Goals

- Observe and model the processes that relate salinity variations to climatic changes in the global cycling of water.
- Understand how these variations influence the general ocean circulation.

Aquarius Mission Background

Sea Surface Salinity (SSS) Studies

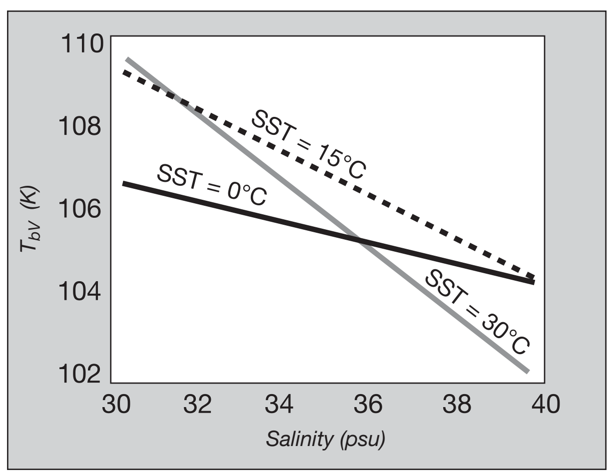
The global mean surface-salinity pattern, as we know it today, reveals fundamental connections to the global water cycle. Lower salinity is generally found in the precipitation-dominated tropics and sub-polar regions, whereas higher salinity is found in the dry subtropics where evaporation dominates. SSS imbalances are seen between basins, with the Atlantic being the saltiest of the major oceans. Alternative theories exist for how this structure is maintained and involve partly a net loss of surface water through excess evaporation from the Atlantic that is carried by the atmosphere and deposited in other basins through rainfall. The enhanced salinity allows denser waters to form in the high-latitude North Atlantic and drive the ocean's overturning 'conveyor' circulation that regulates Earth's climate. Abrupt climate shifts in the recent geological past, sometimes occurring in less than a decade, have been traced to changes in the overturning circulation that are attributed to SSS changes in the sub-polar North Atlantic.

Although the present oceanographic knowledge of the global SSS distribution provides useful climate-modeling information, there is little more that can be done with the existing mean SSS field and estimated annual cycle. The contemporary oceanographic knowledge of salinity at the surface and deep-ocean has been derived from the compendium of ship and some buoy observations acquired over the past 125 years. Nevertheless, the SSS sampling has been sparse, irregular, and largely confined to shipping lanes and the summer season. About 25% of the 1° latitude-longitude squares in the ice-free oceans have never been sampled, including vast regions of the Southern Hemisphere, and greater than 73% have fewer than 10 observations. Global satellite observations are essential to advance the present modeling and physical understanding because they are the only means to portray the evolving global synoptic SSS in conjunction with simultaneously available observations of precipitation, evaporation, wind, surface currents, sea ice changes, and SST.

Aquarius Goals and Objectives

The Aquarius mission responds to this need for global observation of SSS. Its science goals are to observe and model the processes that relate salinity variations to climatic changes in the global cycling of water and to understand how these variations influence the general ocean circulation. By measuring salinity globally and synoptically for three years, Aquarius is expected to provide an unprecedented view of the ocean's role in climate and new insights into ocean circulation and mixing processes. Specifically, science objectives and expectations include:

Discovery and Exploration: Aquarius will resolve unknown patterns and variations of the global SSS field, especially in large under-sampled regions. Aquarius will provide an important reference from which longer-term climatic ocean changes will be detected in the future.



T_b varies linearly with SSS, with a different slope and offset as SST increases. Sensitivity to changes in SSS over the range of open ocean conditions is greatest in warm water (0.7 K/psu) and least in cold (0.3 K/psu). The curves in this figure are for the vertical polarized T_{bV} signal, with an incidence angle of 34°.

Water Cycle: Aquarius will measure spatial and temporal salinity variations to determine how the ocean responds to varying evaporation-minus-precipitation (E-P) surface-water fluxes, ice melt and river runoff on seasonal and interannual time scales.

Ocean Circulation and Climate: Aquarius will investigate how salinity variations modify ocean density and influence density-driven circulation and heat flux in three latitude zones:

- *Tropics:* Air-sea interactions and climate-feedback processes, El Niño/La Niña variations.
- *Mid-Latitudes:* Formation processes of surface-mode waters and their subduction into the ocean interior. (Surface-mode waters carry unique surface temperature and salinity signatures to intermediate depths and serve as tracers for ocean interior circulation.)
- *High Latitudes:* Salinity anomalies that influence the ocean's large-scale overturning circulation and have lasting impacts on climate.

Ancillary science objectives include analyzing air-sea CO_2 flux, monitoring sea ice concentration, and retrieving soil moisture while the satellite is over land.

Measurement Objectives and Approach

Aquarius' science objectives are oriented toward large-scale measurements and long time scales such that the mean, seasonal cycle, and interannual variations are resolved. These will be met by providing monthly average global maps with 150-km spacing and the best possible measurement accuracy. Aquarius is designed to provide composite global maps every seven days specifically to achieve further error reduction by objective interpolation into monthly composites. The 7-day global coverage dictated a minimum swath width of about 350 km, and the spatial requirement dictated a maximum footprint size of about 150 km. These two requirements led to the three-beam configuration. The 3-year mission life is required to obtain a robust map of the climatological mean and seasonal cycle as well as to observe interannual variations. Monthly error requirements are < 0.2 practical salinity units (psu). Spatial or temporal averaging can reduce the residual retrieval error further.

The basis for remote sensing of SSS is the dependence of the dielectric constant of sea water on salinity at microwave frequencies. The dielectric constant determines the surface emissivity (ε), and this determines the measurable parameter, the brightness temperature T_b, by the relationship $T_b = \varepsilon(SST)$, where SST is the physical temperature of the seawater. At L-band (1.4 GHz) for values of SSS (32–37 psu) and SST typical of the open ocean, the dynamic range of T_b is ~4 K. The 1.413 GHz frequency was chosen because of its sensitivity to salinity and it is in a protected radio-frequency (RF) band. The SSS sensitivity is almost negligible above 3 GHz. At lower frequencies, the larger antenna size, and ionospheric and RF interference, make the measurement imprac-

Key Aquarius Instrument Facts

Heritage:

L-Band Radiometer: TRMM/TMI, PALS, AMSR, AMSR-E, ESTAR, SLFMR

L-Band Scatterometer: SeaWinds (on QuikSCAT and ADEOS-II), PALS

Instrument Type: L-Band Radiometer and Scatterometer

Scan: 3-beam push broom with > 350-km swath width (current design)

Accuracy: 0.2 psu rms, monthly, at 150-km resolution

Calibration: Global ocean-observing system surface *in situ* salinity observations (>10,000/month)

Duty Cycle: Continuous

Data Rate: 14.6 kbps; 158 MB/day

FOV: ±10.3° (~350 km swath), center displaced 33° off nadir to shadow side of 6 p.m. orbit

Incidence Angle: 29°, 38°, 46° (3 different fixed antenna beams)

Instrument IFOV: 3 beams 5.9°– 7.0° (footprint: 76 km × 94 km, 84 km × 121 km, 97 km × 157 km)

Dimensions:

Instrument: 3.7 m (ht) × 3.7 (diameter), antenna deployed

Antenna aperture: 2.5-m parabolic reflector, offset feeds

Mass: 400 kg (Aquarius Instrument)

Power: 450 W (Aquarius Instrument)

Platform Pointing Requirements (Platform + Instrument, 3σ):

Control: 0.5°

Knowledge: 0.1°

Stability: 0.1°/s (< 1 Hz, > 0.1 Hz)

Temperature Resolution: Radiometer Brightness Temperature (T_b): 0.15 K (calibration), 0.06 K noise equivalent delta temperature (NEΔT)

Temporal Resolution: Minimum 8 samples per month per 150-km square at equator

Thermal Control: Active

Transmission Frequency: Scatterometer at 1.26 GHz, polarimetric

Measured Frequency: Radiometer 1.413 GHz

Repeat Cycle: 7 days, 103 orbits

tical. At L-band frequencies, the penetration depth of the ocean surface is about 1 cm.

Validation Program

The Aquarius Validation Plan is designed to minimize the measurement error of the retrieved salinity data, improve algorithms and monitor the long-term stability of the sensors during the operational phase. The plan will center on an extensive *in situ* surface measurement program. This will be supplemented with additional calibration strategies primarily for monitoring long-term stability of the radiometer and scatterometer, including vicarious calibration techniques, possible stable ground targets, and occasional cold-sky viewing as needed.

Aquarius *in situ* surface-salinity validation data will be obtained from moored and drifting buoys, Volunteer Observing Ships (VOS), and the automated Argo profiling-buoy array. There will be up to 3000 observations per Aquarius 7-day repeat cycle. All systems will be fully automated with routine data telemetry via satellite and data delivery within one day. These measurements will be applied to validate Aquarius SSS retrievals and generate the scientific data set comprising the blended analysis of satellite and *in situ* salinity data.

Aquarius Instrument

This instrument consists of a radiometer operating in the protected passive-frequency band at 1.413 GHz and a scatterometer in the space-radar band at 1.26 GHz. The radiometer is the primary sensor for SSS, and the scatterometer provides a critical correction for surface roughness. Both instruments will be fully polarimetric to provide information to correct for the Faraday rotation from the ionosphere. Aquarius will use a 2.5-m-diameter offset-feed parabolic reflector, with three feed horns providing three beams in a push-broom configuration. These beams are pointed at 24°, 36°, and 40° incidence angles towards the shaded side of the orbit to reduce the effects of solar reflection and radiation. The resultant swath will give complete global coverage in 7 days and enough samples within a month to achieve the accuracy < 0.2 psu through averaging.

The sun-synchronous orbit was selected to provide a stable thermal environment enabling excellent mechanical and electrical stability. Analyses of the reflector, feed, and support structure designs have shown that this assembly will have the structural stability to meet the on-orbit antenna-pointing knowledge of 0.1° (3σ) even during the eclipse periods during the summer solstice. The instrument thermal design will use an active thermal-control system to achieve temperature stability within 0.1º C RMS for the critical front-end components.

Aquarius Instrument URL

aquarius.gsfc.nasa.gov

Key Aquarius Instrument Facts

(cont.)

Sampling Interval: 10 ms (radiometer); < 2 ms (scatterometer)

Spatial Resolution: 76 km × 94 km, 84 km × 121 km, 97 km × 157 km

Spectral Range: 1.413 GHz ±13 MHz bandwidth (passive), 1.26 GHz ± 2 MHz polarimetric (active)

Standard Profile Spacing: Swath gaps ≤ 50 km

Swath: > 350 km

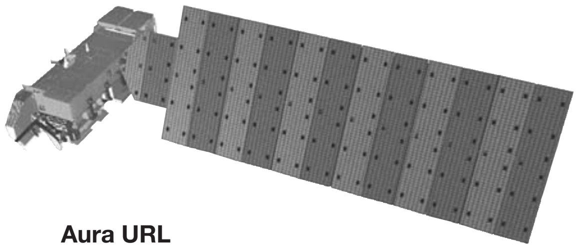
System Temperature: -30º C – +30° C

Aquarius Data Products

Product Name or Grouping	Processing Level	Coverage	Spatial/Temporal Characteristics
Aquarius Instrument			
Raw Radiometer Data	0	Global Ocean poleward to ±77° Latitude	85–133-km horizontal resolution/7-day
Raw Radar Data	0	Global Ocean ±77° Latitude	64–103-km horizontal resolution/7-day
Radiometer Brightness Temperature	1B	Global Ocean ±77° Latitude	85–133-km horizontal resolution/7-day
Radar Backscatter	1B	Global Ocean ±77° Latitude	64–103-km horizontal resolution/7-day
Calibrated/Geolocated SSS	2B	Global Ocean ±77° Latitude	85–133-km horizontal resolution/7-day
Gridded SSS from Aquarius data alone	3B	Global Ocean ±77° Latitude	150-km horizontal resolution/monthly
Gridded SSS merging Aquarius and *in situ* data	3B	Global Ocean ±77° Latitude	150-km horizontal resolution/monthly

Aquarius Data Products

Aura



Aura URL
eos–aura.gsfc.nasa.gov/

Key Aura Facts

Joint with the Netherlands, Finland, and the U.K.

Orbit:
- Type: Polar, sun–synchronous
- Equatorial Crossing: 1:45 p.m.
- Altitude: 705 km
- Inclination: 98.2°
- Period: 100 minutes
- Repeat Cycle: 16 days

Dimensions: 4.70 m × 17.37 m × 6.91 m

Mass: 2967 kg (1200 kg of which are in instruments)

Power: Solar array provides 4800 W. Nickel–hydrogen battery for nighttime operations.

Downlink: X–band for science data; S–band for command and telemetry via Tracking and Data Relay Satellite System (TDRSS) and Deep Space Network to polar ground stations in Alaska and Norway.

Design Life: Nominal mission lifetime of 5 years, with a goal of 6 years of operation.

Contributor: Northrop Grumman Space Technology

Summary

Aura's four instruments study the atmosphere's chemistry and dynamics. Aura's measurements enable us to investigate questions about ozone trends, air–quality changes and their linkage to climate change. Aura's measurements also provide accurate data for predictive models and useful information for local and national agency decision–support systems.

Instruments

- High Resolution Dynamics Limb Sounder (HIRDLS)
- Microwave Limb Sounder (MLS)
- Ozone Monitoring Instrument (OMI)
- Tropospheric Emission Spectrometer (TES)

Points of Contact

- *Aura Project Scientist:* Mark Schoeberl, NASA Goddard Space Flight Center
- *Aura Deputy Project Scientist:* Anne Douglass, NASA Goddard Space Flight Center
- *Aura Deputy Project Scientist:* Joanna Joiner, NASA Goddard Space Flight Center

Other Key Personnel

- *Aura Program Scientist:* Phil DeCola, NASA Headquarters
- *Aura Program Executive:* Lou Schuster, NASA Headquarters
- *Aura Mission Director:* William Guit, NASA Goddard Space Flight Center

Mission Type

Earth Observing System (EOS) Systematic Measurements

Launch

- *Date and Location:* July 15, 2004, from Vandenberg Air Force Base, California
- *Vehicle:* Delta II 7920 rocket

Relevant Science Focus Areas

(see NASA's Earth Science Program section)

- Atmospheric Composition
- Climate Variability and Change
- Weather

Related Applications

(see Applied Sciences Program section)

- Agricultural Efficiency
- Air Quality
- Public Health

Aura Science Goals

The Aura mission seeks to answer three main science questions:

- Is the stratospheric ozone layer recovering?
- What are the processes controlling air quality?
- How is Earth's climate changing?

Aura Mission Background

Aura is the third in the series of large Earth Observing System platforms to be flown by NASA with international contributions. Aura, along with Terra (launched December 1999) and Aqua (launched May 2002), provides an unprecedented view of the global Earth system. The Aura mission consists of four instruments on a common spacecraft (the same bus design as for Aqua) designed to provide the essential services for the instruments.

Aura is part of the A–Train of satellites, which, when the formation is complete, will include at least four other NASA missions—Aqua, Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO), CloudSat, and the Orbiting Carbon Observatory (OCO)—as well as a French Centre National d'Etudes Spatiales (CNES) mission called Polarization and Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar (PARASOL). Aura is the trailing spacecraft in the formation and lags 15 minutes behind Aqua. While each satellite has an independent science mission, measurements from the various spacecraft can also be combined. These complementary satellite observations will enable scientists to obtain more information than they could if all the various observations were used independently. This offers a new and unprecedented resource for exploring aerosol–chemistry–cloud interactions. See the Earth Observing Program section for more details on the A–Train.

As suggested in part by the name, the objective of the Aura mission is to study the chemistry and dynamics of Earth's atmosphere, with emphasis on the upper troposphere and lower stratosphere (5–20 km altitudes). Aura's measurements enable us to investigate questions about ozone trends and air–quality changes, and their linkages to climate change. They also provide accurate data for predictive models and provide useful information for local and national agency decision–support systems.

Aura Mission Validation

Aura's focus on the troposphere and lower stratosphere presents challenges for validation, because this region exhibits much more spatial and temporal variability than the middle and upper stratosphere. To meet these challenges, the Aura project has adopted a strategy to increase the scientific return from the validation program. Some of the validation activities are embedded within focused science campaigns. These campaigns have been selected to obtain data needed to unravel complex science questions that are linked to the three main Aura science goals. Scientists plan to use the satellite data to understand the overall chemical and meteorological environment during the campaigns. Aircraft measurements are used both to validate Aura data and to address the science by making additional measurements.

This strategy emphasizes the strengths of both focused science campaigns and aircraft measurements. Campaign instruments make constituent measurements that are more complete than can be obtained from satellites. Campaign data are also obtained for much smaller spatial scales and with high temporal resolution compared to satellite data. Aircraft missions, on the other hand, take place a few times each year at most and are limited to a small portion of the globe. The Aura instruments make global observations throughout the year and provide data sets that reveal whether or not the campaign observations are truly representative of the atmosphere's chemistry.

The Aura validation program also capitalizes on routine sources of data such as the ozonesonde network and the Network for the Detection of Atmospheric Composition Change (formerly the Network for Detection of Stratospheric Change, or NDSC). Ground–based radiometers and spectrometers make column measurements similar to those made by instruments flying on Aura. Ground–based lidars measure temperature and some trace–gas constituent profiles. Balloon–borne instruments measure profiles of stratospheric constituents up to 40 km. Smaller balloons carry water–vapor instruments in the tropics to validate Aura's measurements of this important gas. Flights of aircraft, such as the DC–8 (medium altitude) and WB–57 (high altitude), provide tropospheric profiles of ozone, carbon monoxide, and nitrogen species. Aircraft lidars measure profiles of ozone and temperature for long distances along the satellite track. Scientists can also compare profiles of stratospheric constituents from Aura with those from other satellites, including the NASA Upper Atmosphere Research Satellite (UARS), the European Space Agency Environmental Satellite (ESA Envisat), and the Canadian Science Satellite (SCISAT) and use data–assimilation techniques to help identify systematic differences among the data sets. The Aura validation program also includes an instrument development program and field campaigns scheduled between October 2004 and Autumn 2007.

Aura Science Questions

Is the Stratospheric Ozone Layer Recovering?

Ozone is formed naturally in the stratosphere through break–up of oxygen (O_2) molecules by solar UV radiation, followed by the uniting of individual oxygen atoms with O_2 molecules, forming ozone (O_3) molecules. Ozone is destroyed when an ozone molecule combines with an oxygen atom to form two oxygen molecules, or through catalytic cycles involving hydrogen, nitrogen, chlorine, or bromine–containing species. For centuries, the atmosphere has maintained a delicate natural balance between ozone formation and destruction.

In recent years, however, man–made chemicals, such as chlorofluorocarbons (CFCs), have altered the natural balance of ozone chemistry. International agreements, such as the Montreal Protocol and its amendments, have been enacted to control these ozone–destroying chemicals, and recent data show that ozone is being depleted at a slower rate than a decade ago. However, it is too soon to tell if this trend is a result of the international protocols restricting CFC production or whether other factors explain the reduction in the rate of ozone loss.

Information returned from Aura's four instruments helps us answer these questions about ozone. The instruments measure the total ozone column, ozone profiles, and gases important in ozone chemistry. They also measure important sources, radicals, and reservoir gases that play active roles in ozone chemistry. The data gathered help to improve our ability to predict ozone changes and also help us better understand how transport and chemistry impact ozone trends.

What are the Processes Controlling Air Quality?

Agricultural and industrial activity have grown dramatically along with the human population. Consequently, in parts of the world, increased emissions of pollutants have significantly degraded air quality. Respiratory problems and even premature deaths due to air pollution occur in urban and some rural areas of both industrialized and developing countries. Widespread burning for agricultural purposes (biomass burning) and forest fires also contribute to poor air quality, particularly in the tropics. The list of culprits contributing to the degradation of air quality includes tropospheric ozone, a toxic gas, and other chemicals whose presence, accompanied by the right atmospheric conditions, leads to the formation of ozone. These so–called ozone precursors include oxides of nitrogen (NO_x), carbon monoxide (CO), methane (CH_4), and other hydrocarbons. Human activities such as biomass burning, inefficient coal combustion, other industrial activities, and vehicular traffic all produce ozone precursors.

The U.S. Environmental Protection Agency (EPA) has identified six pollutants: carbon monoxide, nitrogen dioxide, sulfur dioxide, ozone, lead, and particulates (aerosols). Of these six pollutants, ozone has proven the most difficult to control. Ozone chemistry is complex, making it difficult to quantify the contributions to poor local air quality. Pollutant–emission inventories needed for predicting air quality are uncertain by as much as 50%. Also uncertain is the amount of ozone that enters the troposphere from the stratosphere.

For local governments struggling to meet national air–quality standards, knowing more about the sources and transport of air pollutants has become an important issue. Most pollution sources are local, but satellite observations show that winds can carry pollutants great distances, for example from the western and mid–western states to the east coast of the United States and sometimes even from one continent to another. We have yet to quantify accurately the extent of inter–regional and inter–continental pollution transport.

Aura Instruments

HIRDLS

High Resolution Dynamics Limb Sounder

HIRDLS is an advanced 21–channel infrared radiometer measuring the 6–17–μm thermal emission of Earth's limb designed to provide critical information on atmospheric chemistry and climate. It provides accurate measurements of trace gases, temperature, and aerosols in the upper troposphere, stratosphere, and mesosphere, with daily global coverage at high vertical resolution.

MLS

Microwave Limb Sounder

MLS is an advanced microwave radiometer that measures microwave emission from the Earth's limb in five broad spectral bands. MLS measures trace gases at lower altitudes and with better precision and accuracy than its predecessor on UARS. MLS can provide reliable measurements even in the presence of cirrus clouds and dense volcanic aerosols.

OMI

Ozone Monitoring Instrument

OMI is a nadir–viewing wide–field imaging spectroradiometer that serves as Aura's primary instrument for tracking global ozone change and continues the high quality column–ozone record begun in 1970 by the Nimbus–4 BUV. OMI measures backscattered ultraviolet and visible radiation and provides daily global coverage of most of Earth's atmosphere. Data returned permit modeling of air pollution on urban–to–super–regional scales.

TES

Tropospheric Emission Spectrometer

TES is a high–spectral–resolution infrared–imaging Fourier–transform spectrometer that generates three–dimensional profiles on a global scale of most infrared–active species from Earth's surface to the lower stratosphere.

The Aura instruments are designed to study tropospheric chemistry. Together these instruments provide global monitoring of air pollution on a daily basis and measure five out of the six criteria pollutants identified by the Environmental Protection Agency. Aura provides data of suitable accuracy to improve industrial emission inventories and also helps distinguish between industrial and natural sources. Information provided by Aura may lead to improvements in the accuracy of air–quality forecast models.

How is Earth's Climate Changing?

Carbon dioxide and other gases trap infrared radiation that would otherwise escape to space. This phenomenon, called the greenhouse effect, contributes to making the Earth habitable. Increased atmospheric emissions of trace gases that trap infrared radiation from industrial and agricultural activities are causing climate change. Quantities of many of these gases in the atmosphere have increased and this has added to the greenhouse effect. During the 20^{th} century, the global mean lower tropospheric temperature increased by more than 0.4° C. This increase is thought to be greater than during any other century in the last 1000 years.

Improved knowledge of the sources, sinks, and the distribution of greenhouse gases is needed for accurate predictions of climate change. Aura measures greenhouse gases such as methane, water vapor, and ozone in the troposphere and lower stratosphere. Aura also measures both absorbing and reflecting aerosols in the lower stratosphere and lower troposphere, measures upper tropospheric water-vapor and cloud-ice concentrations, and makes high-vertical-resolution measurements of some greenhouse gases in a broad swath (down to the clouds) across the tropical upwelling region. All of these measurements contribute key data for climate modeling and prediction.

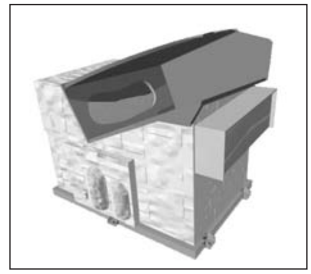
Instrument Descriptions

Each of Aura's four instruments makes important contributions to answering the three science questions described above. The goal with Aura is to achieve 'synergy'—meaning that more information about the condition of the Earth is obtained from the combined observations of the four instruments than would be possible from the sum of the observations taken independently. The four instruments were carefully designed to achieve the overall mission objectives. Each has different fields of view and complementary capabilities.

HIRDLS

High Resolution Dynamics Limb Sounder

HIRDLS Background



HIRDLS is an advanced 21–channel infrared radiometer observing the 6–17 μm thermal emission of the Earth's limb and designed to provide critical information on atmospheric chemistry and climate. It provides accurate measurements of trace gases, temperature, and aerosols in the upper troposphere, the stratosphere, and the mesosphere, with daily near–global coverage at high vertical resolution. HIRDLS looks backward and to the side away from the Sun and scans vertically. Very precise gyroscopes provide instrument–pointing information for HIRDLS. To detect the weak infrared radiation from the Earth's limb, HIRDLS detectors must be kept at temperatures below liquid nitrogen. An advanced cryogenic refrigerator is used to keep the detectors cool.

The University of Colorado, Oxford University (U.K.), the National Center for Atmospheric Research (NCAR), and Rutherford Appleton Laboratory (U.K.) designed the HIRDLS instrument. Lockheed Martin built and integrated the instrument subsystems. The National Environmental Research Council funded the U.K.'s participation.

HIRDLS Contributions to Science Questions

Is the Stratospheric Ozone Level Recovering?

The largest ozone depletions occur over the poles in the lower stratosphere during winter. Therefore, HIRDLS makes concentrated measurements in the northern polar region and retrieves high–vertical–resolution daytime and nighttime ozone profiles over the poles.

HIRDLS also measures NO_2, HNO_3, and CFCs, all gases that play a role in stratospheric ozone depletion. Although international agreements have banned their production, CFCs are long–lived and will remain in the stratosphere for several more decades. By measuring profiles of the long–lived gases, from the upper troposphere into the stratosphere, HIRDLS can assess the transport of air from the troposphere into the stratosphere.

What are the Processes Controlling Air Quality?

HIRDLS measures ozone, nitric acid, and water vapor in the upper troposphere and lower stratosphere. With these measurements, scientists can estimate the amount of stratospheric air that descends into the troposphere and this allows scientists to better distinguish between natural ozone sources and pollution originating from man–made sources. This is an important step forward in quantifying the level at which human activities are impacting the air we breathe.

How is Earth's Climate Changing?

HIRDLS measures water vapor and ozone. Accurate measurement of greenhouse gases such as these are important because scientists input this information into models they use to predict climate change. The more accurate the information that goes into these models, the more accurate and useful the resulting predictions will be. HIRDLS is also able to distinguish between aerosol types that absorb or reflect incoming solar radiation and can map high thin cirrus clouds that reflect solar radiation. This new information allows scientists to better understand how to represent aerosols and thin cirrus clouds in climate models.

HIRDLS Principal Investigators

John Barnett, Oxford University (U.K.)

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HIRDLS URLs

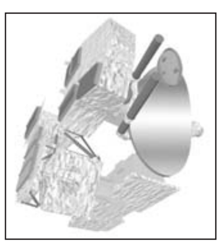
www.eos.ucar.edu/hirdls/
www.atm.ox.ac.uk/hirdls/

MLS

Microwave Limb Sounder

MLS Background

MLS is an advanced microwave radiometer that measures microwave emission from the Earth's limb in five broad spectral bands. These bands are centered at 118 (dual polarization), 190, 240, 640 GHz, and 2.5 THz (dual polarization). MLS can measure trace gases at lower altitudes and with better precision and accuracy than its predecessor on UARS. In addition, MLS obtains trace–gas profiles with a typical vertical resolution of 3 km and has a unique ability to measure trace gases in the presence of ice clouds and volcanic aerosols. MLS pioneers the use of planar diodes and monolithic millimeter–wave integrated circuits to make the instrument more reliable and resilient to launch vibration. MLS looks outward from



Key HIRDLS Facts

Heritage: Limb Radiance Inversion Radiometer (LRIR); Limb Infrared Monitor of the Stratosphere (LIMS) and Stratospheric and Mesospheric Sounder (SAMS); Improved Stratospheric and Mesospheric Sounder (ISAMS), and Cryogenic Limb Array Etalon Spectrometer (CLAES)

Instrument Type: Limb viewing vertical scanning radiometer*

Spectral Range: 6–17 μm, using 21 channels

Scan Type: Vertical limb scans at fixed position*

Scan Range: Elevation, 22.1° to 27.3° below horizontal, +43° on anti–sun side

Dimensions: 149.9 cm × 118.5 cm × 130.2 cm

Detector IFOV: 1.25 km vertical × 10 km horizontal

Duty Cycle: 100%

Power: 262 W (average), 365 W (peak)

Data Rate: 70 kbps

Thermal Control: Detector cooler, Stirling–cycle, heaters, surface coatings, radiator panel

Contributors

Instrument Design: University of Colorado, Oxford University (U.K.), National Center for Atmospheric Research (NCAR), and Rutherford Appleton Laboratory (U.K.)

Instrument Assembly and Integration: Lockheed Martin built and integrated instruments

Funding: National Environmental Research Council (U.K.)

* HIRDLS was originally designed to scan vertically at seven different horizontal positions across the satellite track. Unfortunately, the horizontal scanning capability was lost during launch and the instrument now can only scan vertically at a fixed position.

the front of the spacecraft and obtains vertical scans of the limb. NASA's Jet Propulsion Laboratory (JPL) developed, built, tested, and operates MLS.

MLS Contributions to Science Questions

Is the Stratospheric Ozone Layer Recovering?

MLS continues the ClO and HCl measurements made by UARS. These measurements provide important information on the rate at which stratospheric chlorine is destroying ozone and the total chlorine loading of the stratosphere. MLS provides the first global measurements of the stratospheric hydroxyl (OH) and hydroperoxy (HO_2) radicals that are part of the hydrogen catalytic cycle for ozone destruction. In addition, MLS measures bromine monoxide (BrO), a powerful ozone–destroying radical with both manmade and naturally occurring sources.

MLS measurements of ClO and HCl are especially important in the polar winters. Taken together, these measurements help scientists determine what fraction of stable chlorine reservoirs (HCl) is converted to the ozone–destroying radicals (ClO). Since recent research results indicate that the Arctic stratosphere may now be at a threshold for more severe ozone loss due to climate change, the MLS data are of critical importance for understanding observed changes in Arctic winter ozone.

What are the Processes Controlling Air Quality?

MLS measures carbon monoxide (CO) and ozone in the upper troposphere. CO is normally created in the lower troposphere by incomplete burning of hydrocarbons and is an ozone precursor. When scientists observe heightened concentrations of CO and ozone at the higher levels of the troposphere, it is an indicator of strong vertical transport in the troposphere. These observations can serve as a useful tool for tracking the movement of polluted air masses in the atmosphere.

How is Earth's Climate Changing?

MLS makes measurements of upper tropospheric and lower stratospheric water vapor, ice content, and temperature. Accurate measurements of all of these constituents are needed to help scientists create models that can predict how the Earth's climate is likely to change in the future. MLS also measures ozone and nitrous oxide (N_2O)—both important greenhouse gases—in the upper troposphere and lower stratosphere.

MLS Principal Investigator

Nathaniel Livesey, NASA Jet Propulsion Laboratory/California Institute of Technology

MLS URL

mls.jpl.nasa.gov/

Key MLS Facts

Heritage: Microwave Limb Sounder (MLS)

Instrument Type: Microwave radiometer

Scan Type: Vertical limb scan in plane of orbit, done by moving reflector antenna

Calibration: Views 'blackbody' target and 'cold' space with each limb scan

Spectral Bands: Broad bands centered near 118, 190, 240, and 640 GHz and 2.5 THz

Spatial Resolution: Measurements are performed along the suborbital track, and resolution varies for different parameters; 5–km cross–track × ~200–km along–track × 3–km vertical are typical values

Dimensions: 150 cm × 190 cm × 180 cm (GHz sensor); 80 cm × 100 cm × 110 cm (THz sensor); 160 cm × 50 cm × 30 cm (spectrometer)

Mass: 455 kg

Duty Cycle: 100%

Power: 544 W full–on

Data Rate: 100 kbps

Thermal Control: Via radiators and louvers to space as well as heaters

Thermal Operating Range: 10–35° C

FOV: Boresight 60–70° relative to nadir, in plane of orbit

Instantaneous FOV at 640 GHz: 1.5 km vertical × 3 km cross–track × 200 km along–track at the limb tangent point

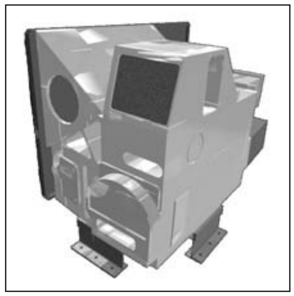
Pointing Requirements (platform+instrument, 3σ):
Control: 36 arcsec
Knowledge: 1 arcsec per s
Stability: 72 arcsec per 30 s
Jitter: 2.7 arcsec per 1/6 s

Contributor: NASA JPL developed, built, tested, and operated MLS; U.K. University of Edinburgh contributed to data processing algorithms and validation.

OMI

Ozone Monitoring Instrument

OMI Background



OMI is an advanced hyperspectral imaging spectrometer with a 114º field of view. Its nadir spatial resolution ranges from 13 km × 24 km to 13 km × 48 km for ozone profiles. It has a 2600–km viewing swath that runs perpendicular to the orbit track so that OMI's swaths almost touch at the equator, enabling complete coverage of the sunlit portion of the atmosphere each day. OMI contains two spectrometers: one measures the UV in the wavelength range of 270–380 nm, while the other measures the visible in the range of 350–500 nm. Both spectrometers have a bandpass of about 0.5 nm with spectral sampling over the range 0.15–0.32 nm/pixel, depending on wavelength. OMI uses a charge–coupled device (CCD) solid–state detector array to provide extended spectral coverage for each pixel across the measurement swath.

OMI is Aura's primary instrument for tracking global ozone change and continues the high–quality column–ozone record begun in 1970 by the Nimbus–4 BUV. Because OMI has a broader wavelength range and better spectral resolution than previous instruments, i.e., OMI's horizontal resolution is about four times greater than that of TOMS, OMI can also measure column amounts of trace gases important to ozone chemistry and air quality. The data from OMI can be used to map aerosols and estimate ultraviolet radiation reaching Earth's surface.

OMI was built by Dutch Space and TNO TPD in the Netherlands in co–operation with Finnish VTT and Patria Advanced Solutions Ltd. KNMI (Royal Netherlands Meteorological Institute) is the Principal Investigator Institute. Overall responsibility for the OMI mission lies with the Netherlands Agency for Aerospace Programmes (NIVR), with the participation of the Finnish Meteorological Institute (FMI).

OMI Contributions to Science Questions

Is the Stratospheric Ozone Layer Recovering?

OMI continues the 25–year satellite ozone record of SBUV and TOMS, mapping global ozone change (column amounts and profiles); data returned is used to support congressionally mandated and international ozone assessments. OMI has a broader wavelength range and better spectral resolution than previous ozone measuring instruments, and this should help scientists resolve differences among satellite and ground–based ozone measurements. OMI also measures the atmospheric column amounts of radicals such as nitrogen dioxide (NO_2), bromine oxide (BrO), and chlorine dioxide (OClO).

Key OMI Facts

Heritage: Total Ozone Mapping Spectrometer (TOMS), Solar Backscatter Ultraviolet (SBUV), Global Ozone Monitoring Experiment (GOME), Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY), Global Ozone Monitoring by Occultation of Stars (GOMOS)

Instrument Type: Wide–field imaging spectroradiometer

Scan Type: Non–scanning

Spectral Bands:
Visible: 350–500 nm
UV–1: 270–314 nm
UV–2: 306–380 nm

Spectral Resolution: 0.63–0.42 nm full width at half maximum (FWHM)

Spectral Sampling: 2–3 for FWHM

Dimensions: 50 cm × 40 cm × 35 cm

Mass: 46.06 kg

Power: 56 W (operational average)

Duty Cycle: 60 minutes on daylight side

Data Rate: 0.77 Mbps (average)

Telescope FOV: 114º (2600 km on ground)

IFOV: 3 km, binned to 13 km × 24 km

Detector: CCD, 780 × 576 (spectral × spatial) pixels

Pointing (arcsec) (platform+instrument, pitch:roll:yaw, 3σ):
Accuracy: 275:275:275
Knowledge: 28:28:28
Stability (6 s): 28:28:28

Calibration: A white–light source is included onboard, as well as Light–Emitting Diodes (LEDs), a multi–surface solar–calibration diffuser, and a scrambler that scrambles the polarization from the back–scattered radiation.

Contributors

Industry Design and Assembly: Dutch Space (Netherlands), TNO (Netherlands), VTT (Finland), and Patria Advanced Solutions Ltd. (Finland)

Space Agencies and Funding: NIVR (Netherlands), with participation of FMI (Finland)

Responsible Centers: KNMI (Netherlands) and FMI (Finland)

What are the Processes Controlling Air Quality?

Tropospheric ozone, nitrogen dioxide, sulfur dioxide, and aerosols are four of the U.S. Environmental Protection Agency's six criteria pollutants. OMI maps tropospheric column totals of sulfur dioxide and aerosols. Scientists can take advantage of the synergistic nature of the Aura instruments and combine measurements from OMI, MLS, and HIRDLS, to produce maps of tropospheric ozone and nitrogen dioxide. In addition, OMI also measures the tropospheric ozone precursor formaldehyde. Scientists plan to use OMI measurements of ozone and cloud cover to derive the amount of ultraviolet (UV) radiation reaching Earth's surface. The National Weather Service will use OMI data to forecast high UV index days for public health awareness.

How is Earth's Climate Changing?

OMI tracks ozone, dust, smoke, biomass burning, and industrial aerosols in the troposphere. OMI's UV measurements allow scientists to better distinguish reflecting and absorbing aerosols, another important step forward in helping scientists more accurately represent aerosols in climate models.

OMI Principal Investigators

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Johanna Tamminen, Finnish Meteorological Institute (Finland)

Ernest Hilsenrath, NASA Goddard Space Flight Center (U.S.)

OMI URL

www.knmi.nl/omi

TES

Tropospheric Emission Spectrometer

TES Background

TES is a high–resolution infrared–imaging Fourier Transform Spectrometer with spectral coverage of 3.2–15.4 µm at a spectral resolution of 0.025/cm. The instrument can provide information on essentially almost all radiatively active gases in Earth's lower atmosphere, both night and day. TES makes both limb and nadir observations. In the limb mode, TES has a height resolution of 2.3 km, with coverage from the surface to 34 km altitude. In the nadir mode, TES has a spatial resolution of 5.3 km × 8.5 km. The instrument can be pointed to any target within 45° of the local vertical. TES uses the same cryogenic refrigeration system described under HIRDLS to allow for detection of weak infrared radiation from Earth's atmosphere.

Key TES Facts

Heritage: Atmospheric Trace Molecule Spectroscopy experiment (ATMOS), Stratospheric CRyogenic Infrared Balloon Experiment (SCRIBE), Airborne Emission Spectrometer (AES)

Instrument Type: Infrared–Imaging Fourier Transform Spectrometer

Scan Type: Both limb and nadir scanning; fully targetable

Spectral Range: 3.2–15.4 µm, with four single–line arrays optimized for different spectral regions

Maximum Sampling Time: 16 s w/signal–to–noise ratio of up to 200:1

Swath: 5.3 km × 8.5 km

Spatial Resolution: 0.53 km × 5.3 km

Dimensions:
Stowed: 140 cm × 130 cm × 135 cm
Deployed: 304 cm × 130 cm × 135 cm

Mass: 385 kg

Thermal Control: 2 pulse–tube coolers, heater, radiators

Thermal Operating Range: 0–30° C

Power: 334 W

Duty Cycle: Variable

Data Rate: 6.2 Mbps (peak); 4.9 Mbps (average)

FOV: +45° to –72° along–track, ±45° cross–track

Instrument IFOV: 12 × 7.5 mrad

Pointing Requirements (platform+instrument, 3σ):
Control: 156 arcsec (pitch)
Knowledge: 124 arcsec
Stability: 156 arcsec (over 50 s)

Calibration: On–board 340–K blackbody; cold space.

Responsible Center: NASA JPL

TES measures tropospheric ozone and many other gases important to tropospheric pollution. The presence of clouds in the atmosphere makes obtaining satellite tropospheric chemical observations more difficult, but the ability to make observations in the nadir and across the limb circumvents this problem. This observation capability provides measurements of the entire lower atmosphere, from the surface to the stratosphere.

TES Contributions to Science Questions

Is the Stratospheric Ozone Layer Recovering?

TES limb measurements extend from Earth's surface to the middle stratosphere, and the TES spectral range overlaps the spectral range of HIRDLS. As a result, TES's high–resolution spectra allow scientists to make measurements of some additional stratospheric constituents and also improve HIRDLS measurements of species common to both instruments.

What are the Processes Controlling Air Quality?

This is TES's primary focus. It measures the distribution of gases in the troposphere. TES can provide simultaneous measurements of tropospheric ozone and key gases involved in tropospheric ozone chemistry, such as CH_4, HNO_3 and CO. This information will serve as input for regional ozone–pollution models and will help to improve the accuracy and utility of these models.

How is Earth's Climate Changing?

TES measures tropospheric water vapor, methane, ozone and aerosols, all of which are relevant to climate change. In addition to this, other gases important to climate change can be retrieved from the TES spectra.

TES Principal Investigator

Reinhard Beer, NASA Jet Propulsion Laboratory/California Institute of Technology

TES URL

tes.jpl.nasa.gov/

Aura References

Schoeberl, M. R., A. R. Douglass, and E. Hilsenrath, eds., 2006: Special Issue on the EOS Aura Mission. *IEEE Trans. Geosci. Remote Sens.*, **44 (5)**, 1061–1397.

HIRDLS References

Barnett, J. J., A. G. Darbyshire, C. L. Hepplewhite, C. W. P. Palmer, F. Row, P. Venters, R. E. J. Watkins, J. G. Whitney, J. C. Gille, and B. R. Johnson, 1998: Pre–launch calibration of the HIRDLS instrument. *SPIE*, **3437**, 137–146.

Barnett, J. J., P. Venters, and J. C. Gille, 1998: Direct measurement of geopotential height by the HIRDLS instrument. *Adv. Space Res.*, **22**, 1497–1500.

Dials, M. A., J. C. Gille, J. J. Barnett, and J. G. Whitney, 1998: Description of the High Resolution Dynamics Limb Sounder (HIRDLS) instrument. *SPIE*, **3437**, 84–91.

Edwards, D., J. Gille, P. Bailey, and J. Barnett, 1995: Selection of the sounding channels for the High Resolution Dynamics Limb Sounder. *Appl. Optics*, **34**, 7006–7017.

Gille, J., and J. Barnett, 1992: The High–Resolution Dynamics Limb Sounder (HIRDLS). An instrument for the study of global change, in J. Gille and G. Visconti, eds., *The Use of EOS for Studies of Atmospheric Physics*, North–Holland, 433–450.

Gille, J., J. Barnett, M. Coffey, W. Mankin, B. Johnson, M. Dials, J. Whitney, D. Woodard, P. Arter, and W. Rudolf, 1994: The High Resolution Dynamics Limb Sounder (HIRDLS) for the Earth Observing System. *SPIE*, **2266**, 330–339.

Gille, J., and J. Barnett, 1996: Conceptual design of the High Resolution Dynamics Limb Sounder (HIRDLS) for the EOS Chemistry Mission. *SPIE*, **2830**, 190–201.

Johnson, B. R., W. G. Mankin, and J. C. Gille, 1998: Description of the HIRDLS Radiometric Model (HIRAM). *SPIE*, **3437**, 147–155.

Palmer, C., and J. Whitney, 1996: The radiometric calibration budget for the High–Resolution Dynamics Limb Sounder. *J. Atmos. Ocean. Tech.*, **13**, 336–348.

MLS References

Canty, T., H. M. Pickett, R. J. Salawitch, K. W. Jucks, W. A. Traub, and J. W. Waters, 2006: Stratospheric and mesospheric HO_X: Results from Aura MLS and FIRS–2. *Geophys. Res. Lett.*, in press.

Cofield, R. E., and P. C. Stek, 2006: Design and field-of-view calibration of 114–660 GHz optics of the Earth Observing System Microwave Limb Sounder. *IEEE Trans. Geosci. Remote Sens.*, **44**, 1166–1181.

Cuddy, D. T., M. Echeverri, P. A. Wagner, A. Hanzel, and R. A. Fuller, 2006: EOS MLS science data processing system: A description of architecture and capabilities. *IEEE Trans. Geosci. Remote Sens.*, **44**, 1192–1198.

Davis, C. P., D. L. Wu, C. Emde, J. H. Jiang, R. E. Cofield, and R. S. Harwood, 2005: Cirrus induced polarization in 122 GHz Aura Microwave Limb Sounder Radiances. *Geophys. Res. Lett.*, **32**, L14806, doi:10.1029/2005GL022681.

Filipiak, M. J., R. S. Harwood, J. H. Jiang, Q. Li, N. J. Livesey, G. L. Manney, W. G. Read, M. J. Schwartz, J. W. Waters, and D. L. Wu, 2005: Carbon monoxide measured by the EOS Microwave Limb Sounder on Aura: First results. *Geophys. Res. Lett.*, **32**, L14825, doi:1029/2005GL022765.

Froidevaux, L., N. J. Livesey, W. G. Read, Y. B. Jiang, C. Jimenez, *et al.*, 2006: Early validation analyses of atmospheric profiles from EOS MLS on the Aura satellite. *IEEE Trans. Geosci. Remote Sens.*, **44 (5)**, 1106–1121.

Fu, R., Y. Hu, J. S. Wright, J. H. Jiang, R. E. Dickinson, M. Chen, M. Filipiak, W. G. Read, J. W. Waters, and D. L. Wu, 2006: Short circuit of water vapor and polluted air to the global stratosphere by convective transport over the Tibetan Plateau. *Proc. Nat. Acad. Sci.*, **103**, 5664–5669.

Jarnot, R. F., V. S. Perun, and M. J. Schwartz, 2006: Radiometric and spectral performance and calibration of the GHz bands of EOS MLS. *IEEE Trans. Geosci. Remote Sens.*, **44**, 1131–1143.

Li, J.-L., D. E. Waliser, J. H. Jiang, D. L. Wu, W. G. Read, J. W. Waters, A. M. Tompkins, L. J. Donner, J.-D. Chern, W.-K. Tao, R. Atlas, Y. Gu, K. N. Liou, A. Del Genio, M. Khairoutdinov, and A. Gettelman, 2005: Comparisons of EOS MLS cloud ice measurements with ECMWF analyses and GCM simulations: Initial results. *Geophys. Res. Lett.*, **32**, L18710, doi:10.1029/2005GL023788.

Li, Q. B., J. H. Jiang, D. L. Wu, W. G. Read, N. J. Livesey, J. W. Waters, Y. Zhang, B. Wang, M. J. Filipiak, C. P. Davis, S. Turquety, S. Wu, R. J. Park, R. M. Yantosca, and D. J. Jacob, 2005: Convective outflow of South Asian pollution: A global CTM simulation compared with EOS MLS observations. *Geophys. Res. Lett.*, **32 (14)**, L14826, doi:10.1029/2005GL022762.

Limpasuvan, V., D. L. Wu, M. J. Schwartz, J. W. Waters, Q. Wu, and T. L. Killeen, 2005: The two-day wave in EOS MLS temperature and wind measurements during 2004–2005 winter. *Geophys. Res. Lett.*, **32**, L17809, doi:10.1029/2005GL023396.

Livesey, N. J., W. V. Snyder, W. G. Read, and P. A. Wagner, 2006: Retrieval algorithms for the EOS Microwave Limb Sounder (MLS) instrument. *IEEE Trans. Geosci. Remote Sens.*, **44**, 1144–1155.

Manney, G. L., N. J. Livesey, C. J. Jimenez, H. C. Pumphrey, M. L. Santee, I. A. MacKenzie, and J. W. Waters, 2006: EOS Microwave Limb Sounder Observations of ‘frozen-in’ anticyclone air in Arctic summer. *Geophys. Res. Lett.*, in press.

Manney, G. L., M. L. Santee, L. Froidevaux, K. Hoppel, N. J. Livesey, and J. W. Waters, 2006: EOS MLS observations of ozone loss in the 2004–2005 Arctic winter. *Geophys. Res. Lett.*, **33**, L04892, doi:10.1029/2005GL024494.

Manney, G. L., M. L. Santee, N. J. Livesey, L. Froidevaux, W. G. Read, H. C. Pumphrey, J. W. Waters, and S. Pawson, 2005: EOS Microwave Limb Sounder observations of the Antarctic polar vortex breakup in 2004. *Geophys. Res. Lett.*, **32**, L12811, doi:10.1029/2005GL022823.

Pickett, H. M., 2006: Microwave Limb Sounder THz Module on Aura. *IEEE Trans. Geosci. Remote Sens.*, **44**, 1122–1130.

Pickett, H. M., B. J. Drouin, T. Canty, L. J. Kovalenko, R. J. Salawitch, N. J. Livesey, W. G. Read, J. W. Waters, K. W. Jucks, and W. A. Traub, 2006: Validation of Aura MLS HO_X measurements with remote-sensing balloon instruments. *Geophys. Res. Lett.*, **33**, L01808, doi:10.1029/2005GL024442.

Pumphrey, H. C., C. J. Jimenez, and J. W. Waters, 2006: Measurement of HCN in the middle atmosphere by EOS MLS. *Geophys. Res. Lett.*, in press.

Read, W. G., Z. Shippony, M. J. Schwartz, N. J. Livesey, and W. V. Snyder, 2006: The clear-sky unpolarized forward model for the EOS Microwave Limb Sounder (MLS). *IEEE Trans. Geosci. Remote Sens.*, **44**, 1367–1379.

Santee, M. L, G. L. Manney, N. J. Livesey, L. Froidevaux, H. C. Pumphrey, W. G. Read, M. J. Schwartz, and J. W. Waters, 2005: Polar processing and development of the 2004 Antarctic ozone hole: First results from Aura MLS. *Geophys. Res. Lett.*, **32**, L12817, doi:1029/2005GL022582.

Schoeberl, M. R., B. N. Duncan, A. R. Douglass, J. W. Waters, N. J. Livesey, W. G. Read, and M. J. Filipiak, 2006: The carbon monoxide tape recorder. *Geophys. Res. Lett.*, in press.

Schoeberl, M. R., S. R. Kawa, A. R. Douglass, T. J. McGee, E. V. Browell, J. W. Waters, N. J. Livesey, W. G. Read, L. Froidevaux, M. L. Santee, H. C. Pumphrey, L. R. Lait, and L. Twigg, 2006: Chemical observations of a polar vortex intrusion. *J. Geophys. Res.*, in press.

Schwartz, M. J., W. G. Read, and W. V. Snyder, 2006: Polarized radiative transfer for Zeeman-split oxygen lines in the EOS MLS forward model. *IEEE Trans. Geosci. Remote Sens.*, **44**, 1182–1191.

Su, H., W. G. Read, J. H. Jiang, J. W. Waters, D. L. Wu, and E. J. Fetzer, 2006: Enhanced positive water vapor feedback associated with tropical deep convection: New evidence from Aura MLS. *Geophys. Res. Lett.*, **33**, L05709, doi:10.1029/2005GL025505.

Waters, J. W., 1993: Microwave limb sounding, in M. A. Janssen, ed., *Atmospheric Remote Sensing*, John Wiley, New York, 383–496.

Waters, J. W., L. Froidevaux, R. S. Harwood, R. F. Jarnot, H. M. Pickett, *et al.*, 2006: The Earth Observing System Microwave Limb Sounder (EOS MLS) on the Aura satellite. *IEEE Trans. Geosci. Remote Sens.*, **44**, 1075–1092.

Wu, D. L., J. H. Jiang, and C. P. Davis, 2006: EOS MLS cloud ice measurements and cloudy-sky radiative transfer model. *IEEE Trans. Geosci. Remote Sens.*, **44**, 1156–1165.

Ziemke, J. R., S. Chandra, B. N. Duncan, L. Froidevaux, P. K. Bhartia, P. F. Levelt, and J. W. Waters., 2006: Tropospheric ozone determined from Aura OMI and MLS: Evaluation of measurements and comparison with the Global Modeling Initiative's Chemical Tracer Model. *J. Geophys. Res.*, in press.

OMI References

Acarreta, J. R., J. F. de Haan, and P. Stammes, 2004: Cloud pressure retrieval using the O_2-O_2 absorption band at 477 nm. *J. Geophys. Res.*, **109**, No. D5, D05204, doi:10.1029/2003JD003915.

Boersma, K. F., H. J. Eskes, and E. J. Brinksma, 2004: Error analysis for tropospheric NO_2 retrieval from space. *J. Geophys. Res.*, **109**, No. D4, D04311, doi:10.1029/2003JD003962.

Bucsela, E. J., E. A. Celarier, M. O. Wenig, J. F. Gleason, J. P. Veefkind, K. F. Boersma, and E. Brinksma, 2006: Algorithm for NO_2 vertical column retrieval from the Ozone Monitoring Instrument. *IEEE Trans. Geosci. Remote Sens.*, **44**, 1245–1258.

Dobber, M. R., R. J. Dirksen, R. Voors, G. H. Mount, and P. Levelt, 2005: Ground-based zenith sky abundances and in situ gas cross sections for ozone and nitrogen dioxide with the Earth Observing System Aura Ozone Monitoring Instrument. *Appl. Optics*, **44 (14)**, 2846–2856.

Dobber, M. R., R. J. Dirksen, P. F. Levelt, G. H. J. van den Oord, R. H. M. Voors, et al., 2006: Ozone Monitoring Instrument calibration. *IEEE Trans. Geosci. Remote Sens.*, **44**, 1209–1238.

Joiner, J., and A. P. Vasilkov, 2006: First results from the OMI rotational Raman scattering cloud pressure algorithm. *IEEE Trans. Geosci. Remote Sens.*, **44**, 1272–1282.

Joiner, J., A. P. Vasilkov, K. Yang, and P. K. Bhartia, 2006: Observations over hurricanes from the Ozone Monitoring Instrument. *Geophys. Res. Lett.*, **33**, L06807, doi:10.1029/2005GL025592.

Krotkov, N. A., S. A. Carn, A. J. Krueger, P. K. Bhartia, and K. Yang, 2006: Band residual difference algorithm for retrieval of SO_2 from the Aura Ozone Monitoring Instrument (OMI). *IEEE Trans. Geosci. Remote Sens.*, **44**, 1259–1266.

Leppelmeier, G. W., O. Aulamo, S. Hassinen, A. Malkki, T. Riihisaari, R. Tajakka, J. Tamminen, and A. Tanskanen, 2006: OMI very fast delivery and the Sodankyla satellite data centre. *IEEE Trans. Geosci. Remote Sens.*, **44**, 1283–1287.

Levelt, P. F., P. K. Bhartia, P. Stammes, and K. Chance, 2002: OMI Algorithm Theoretical Basis Document, volume I–IV, August 2002. [Available online at: eospso.gsfc.nasa.gov/eos_homepage/for_scientists/atbd/index.php.]

Levelt, P. F., G. H. J. van den Oord, M. R. Dobber, A. Malkki, H. Visser, *et al.*, 2006: The Ozone Monitoring Instrument. *IEEE Trans. Geosci. Remote Sens.*, **44**, 1093–1101.

Levelt, P. F., E. Hilsenrath, G. W. Leppelmeier, G. H. J. van den Oord, P. K. Bhartia, *et. al.*, 2006: Science objectives of the Ozone Monitoring Instrument. *IEEE Trans. Geosci. Remote Sens.*, **44**, 1199–1208.

van den Oord, G. H. J., N. C. Rozemeijer, V. Schenkelaars, P. F. Levelt, M. R. Dobber, *et al.*, 2006: OMI level 0 to 1b processing and operational aspects. *IEEE Trans. Geosci. Remote Sens.*, **44**, 1380–1397.

Tanskanen, A., N. A. Krotkov, J. R. Herman, and A. Arola, 2006: Surface ultraviolet irradiance from OMI. *IEEE Trans. Geosci. Remote Sens.*, **44**, 1267–1271.

Veefkind, J. P., J. F. de Haan, E. J. Brinksma, M. Kroon, and P. F. Levelt, 2006: Total ozone from the Ozone Monitoring Instrument (OMI) using the DOAS technique. *IEEE Trans. Geosci. Remote Sens.*, **44**, 1239–1244.

Ziemke, J. R., S. Chandra, B. N. Duncan, L. Froidevaux, P. K. Bhartia, P. F. Levelt, and J. W. Waters, 2006: Tropospheric ozone determined from Aura OMI and MLS: Evaluation of measurements and comparison with the Global Modeling Initiative's Chemical Transport Model. *J. Geophys. Res.*, in press.

TES References

Beer, R., T. A. Glavich, and D. M. Rider, 2001: Tropospheric emission spectrometer for the Earth Observing System's Aura satellite. *Appl. Optics*, **40**, 2356–2367.

Beer, R., 2006: TES on the Aura mission: Scientific objectives, measurements and analysis overview. *IEEE Trans. Geosci. Remote Sens.*, **44**, 1102–1105.

Bowman, K. W., T. Steck, H. M. Worden, J. Worden, S. Clough, and C. D. Rodgers, 2002: Capturing time and vertical variability of tropospheric ozone: A study using TES nadir retrievals. *J. Geophys. Res.*, **107**, doi:10.1029/2002JD002150.

Bowman, K. W., H. M. Worden, and R. Beer, 2000: Instrument line shape modeling and correction for off-axis detectors in Fourier transform spectrometry. *Appl. Optics*, **39**, 3763–3773.

Bowman, K. W., C. D. Rodgers, S. S. Kulawik, J. Worden, E. Sarkissian, *et al.*, 2006: Tropospheric Emission Spectrometer: Retrieval method and error analysis. *IEEE Trans. Geosci. Remote Sens.*, **44**, 1297–1307.

Chu, E., D. Tremblay, K. Croft, and A. Griffin, 2006: TES Science Investigator-Led Processing System. *IEEE Trans. Geosci. Remote Sens.*, **44**, 1352–1358.

Clerbaux C., J. Hadji-Lazaro, S. Payan, C. Camy-Peyret, J. Wang, D. P. Edwards, and M. Luo, 2002: Retrieval of CO from nadir remote-sensing measurements in the infrared using four different inversion algorithms. *Appl. Optics*, **41**, 7068–7078.

Clough, S. A., M. W. Shephard, J. Worden, P. D. Brown, H. M. Worden, *et al.*, 2006: Forward model and Jacobians for Tropospheric Emission Spectrometer retrievals. *IEEE Trans. Geosci. Remote Sens.*, **44**, 1308–1323.

Clough, S. A., J. R. Worden, P. D. Brown, M. W. Shephard, C. P. Rinsland, and R. Beer, 2002: Retrieval of tropospheric ozone from simulations of limb spectral radiances as observed from space. *J. Geophys. Res.*, **107**, 10.1029/2001JD001307.

Jones, D. B. A., K. W. Bowman, P. I. Palmer, J. R. Worden, D. J. Jacob, R. N. Hoffman, I. Bey, and R. M. Yantosca, 2003: Potential of observations from the Tropospheric Emission Spectrometer to constrain continental sources of carbon monoxide. *J. Geophys. Res.*, **108**, 10.1029/2003JD003702.

Kulawik, S. S., G. Osterman, D. B. A. Jones, and K. Bowman, 2006: Calculation of altitude-dependent Tikhonov constraints for TES nadir retrievals. *IEEE Trans. Geosci. Remote Sens.*, **44**, 1334–1342.

Kulawik, S. S., H. Worden, G. Osterman, M. Luo, R. Beer, D. Kinnison, K.W. Bowman, J. Worden, A. Eldering, M. Lampel, T. Steck, and C. Rodgers, 2006: TES atmospheric profile retrieval characterization: An orbit of simulated observations. *IEEE Trans. Geosci. Remote Sens.*, **44**, 1324–1333.

Luo, M., R. Beer, D. J. Jacob, J. A. Logan, and C. D. Rodgers, 2002: Simulated observation of tropospheric ozone and CO with the Tropospheric Emission Spectrometer (TES) satellite instrument. *J. Geophys. Res.*, **107**, 10.1029/2001JD000804.

Paradise, S., S. Akopyan, R. C. DeBaca, K. Croft, K. Fry, S. Gluck, D. Ho, B. Koffend, M. Lampel, J. McDuffie, R. Monarrez, H. Nair, S. Poosti, D. Shepard, I. Strickland, D. Tremblay, H. Yun, and J. Zong, 2006: TES ground data system software. *IEEE Trans. Geosci. Remote Sens.*, **44**, 1343–1351.

Sarkissian, E., and K. W. Bowman, 2003: Application of a nonuniform spectral resampling transform in Fourier-transform spectrometry. *Appl. Optics-LP*, **42**, 1122.

Worden, H., R. Beer, K. Bowman, B. Fisher, M. Luo, D. Rider, E. Sarkissian, D. Tremblay, and J. Zong, 2006: TES L1 algorithms: Interferogram processing, geolocation, radiometric and spectral calibration. *IEEE Trans. Geosci. Remote Sens.*, **44**, 1288–1296.

Worden, J., S. Sund-Kulawik, M. W. Shephard, S. A. Clough, H. Worden, K. Bowman, and A. Goldman, 2004: Predicted errors of Tropospheric Emission Spectrometer nadir retrievals from spectral window selection. *J. Geophys. Res.*, **109**, D09308, 10.1029/2004JD004522.

Worden, J. R., K. W. Bowman, and D. B. Jones, 2004: Two-dimensional characterization of atmospheric profile retrievals from limb sounding observations. *J. Quant. Spectrosc. Rad. Transfer*, **86**, 45–71.

Aura Data Products

The data from Aura's four instruments are transmitted from the satellite ground stations and thence to the EOS Data and Operations System (EDOS). From there the raw data from HIRDLS, MLS, and OMI are sent to the Goddard Distributed Active Archive Center (DAAC); raw data from TES are sent to the Langley Research Center (LaRC) DAAC. Each Science Investigator–led Processing System (SIPS) receives data directly from the DAACs and processes it to produce scientific data such as profiles and column amounts of ozone and other important atmospheric species. Each instrument team monitors the data products to ensure that they are of high quality. The data products are then sent back to the DAACs, where they are archived. The DAACs are responsible for distribution of the data to scientists all over the world. Researchers, government agencies, and educators will have unrestricted access to the Aura data via the EOS data gateway. Data seekers can search for, and order data from, any of the EOS DAACs.

- *Goddard DAAC:* daac.gsfc.nasa.gov
- *Langley DAAC:* eosweb.larc.nasa.gov/

Product Name or Grouping	Processing Level	Coverage	Spatial/Temporal Characteristics
HIRDLS *Data Set Start Date: No data released as of May 2006*			
Radiances	1B	Global	70 km horizontal resolution (along track)
Temperature/Pressure Profile	2	Global for altitudes of 7–60 km	70 km horizontal resolution (along track), 1.25 km vertical resolution/ twice daily [day, night]
O_3	2	Global, 7–55 km	70 km horizontal resolution (along track), 1.25 km vertical resolution/ twice daily [day, night]
H_2O Concentration	2	Global, 7–55 km	70 km horizontal resolution (along track), 1.25 km vertical resolution/ twice daily [day, night]
Aerosol Extinction Coefficient (4 Channels)	2	Global, 10–30 km	70 km horizontal resolution (along track), 1.25 km vertical resolution/ twice daily [day, night]
NO_2	2	Global, 20–55 km	70 km horizontal resolution (along track), 1.25 km vertical resolution/ twice daily [day, night]
CH_4 Concentration	2	Global, 10–60 km	70 km horizontal resolution (along track), 1.25 km vertical resolution/ twice daily [day, night]
CFC–11 ($CFCl_3$) Concentration	2	Global, 7–28 km	70 km horizontal resolution (along track), 1.25 km vertical resolution/ twice daily [day, night]
CFC–12 (CF_2Cl_2) Concentration	2	Global, 7–30 km	70 km horizontal resolution (along track), 1.25 km vertical resolution/ twice daily [day, night]
$ClONO_2$	2	Global, 17–40 km	70 km horizontal resolution (along track), 1.25 km vertical resolution/ twice daily [day, night]
Cloud Top Height	2	Global, 7–24 km	70 km horizontal resolution (along track), 250 m vertical resolution/ twice daily [day, night]

Aura Data Products

Product Name or Grouping	Processing Level	Coverage	Spatial/Temporal Characteristics
HNO_3 Concentration	2	Global, 10–40 km	70 km horizontal resolution (along track), 1.25 km vertical resolution/ twice daily [day, night]
N_2O Concentration	2	Global, 10–55 km	70 km horizontal resolution (along track), 1.25 km vertical resolution/ twice daily [day, night]
N_2O_5 Concentration	2	Global, 20–45 km	70 km horizontal resolution (along track), 1.25 km vertical resolution/ twice daily [day, night]
Geopotential Height–Gradient	2	Global, 15–30 km	70 km horizontal resolution (along track)/ twice daily [day, night]
MLS *Data Set Start Date: August 8, 2004*			
Radiances	1B	Global for altitudes of 0–90 km	200 km horizontal resolution (along track), ~0.3–3 km vertical resolution/ twice daily [day, night]
Temperature	2, 3	Global, 5–90 km	200 km horizontal resolution, 2–3 km vertical resolution/ twice daily [day, night]
Geopotential Height	2, 3	Global, 5–90 km	200 km horizontal resolution, 2–3 km vertical resolution/ twice daily [day, night]
Cloud Ice Content	2	Global, 5–20 km	200 km horizontal resolution, 2–3 km vertical resolution/ twice daily [day, night]
H_2O Concentration	2, 3	Global, 5–90 km	200 km horizontal resolution, 2–3 km vertical resolution/ twice daily [day, night]
Relative Humidity (with respect to ice)	2, 3	Global, 5–90 km	200 km horizontal resolution, 2–3 km vertical resolution/ twice daily [day, night]
N_2O Concentration	2, 3	Global, 15–60 km	200 km horizontal resolution, ~3 km vertical resolution/ twice daily [day, night]
CO Concentration (stratosphere and above)	2, 3	Global, 15–90 km	200 km horizontal resolution, ~3 km vertical resolution/ twice daily [day, night]
CO Concentration (upper troposphere)	2, 3	Global, 8–15 km	200 km horizontal resolution, ~3 km vertical resolution/ twice daily [day, night]
O_3 Concentration (stratosphere and above)	2, 3	Global, 15–80 km	200 km horizontal resolution, ~3 km vertical resolution/ twice daily [day, night]
O_3 Concentration (upper troposphere)	2, 3	Global, 8–15 km	200 km horizontal resolution, ~3 km vertical resolution/ twice daily [day, night]

Aura Data Products

Product Name or Grouping	Processing Level	Coverage	Spatial/Temporal Characteristics
MLS			
OH Concentration (upper stratosphere)	2, 3	Global, 30–90 km	200 km horizontal resolution, ~3 km vertical resolution/ twice daily [day, night]
OH Concentration (lower stratosphere)	2, 3	Global, 18–30 km	10° lat. resolution, monthly zonal mean, ~3 km vertical resolution/ twice daily [day, night]
HO_2 Concentration	2, 3	Global, 20–60 km	10° lat. resolution, monthly zonal mean, 5 km vertical resolution/ twice daily [day, night]
BrO Concentration	2, 3	Global, 20–60 km	10° lat. resolution, monthly zonal mean, 5 km vertical resolution/ twice daily [day, night]
ClO Concentration	2, 3	Global, 15–50 km	200 km horizontal resolution, ~3 km vertical resolution/ twice daily [day, night]
HCl Concentration	2, 3	Global, 15–60 km	200 km horizontal resolution, ~3 km vertical resolution/ twice daily [day, night]
HOCl Concentration	2, 3	Global, 20–50 km	10° lat. resolution, monthly zonal mean, 5 km vertical resolution/ twice daily [day, night]
HNO_3 Concentration	2, 3	Global, 10–50 km	200 km horizontal resolution, ~3 km vertical resolution/ twice daily [day, night]
HCN Concentration	2, 3	Global, 25–65 km	horizontal resolution: 5° lat. for weekly zonal mean, 200 km for 30–40 km, ~3 km vertical resolution/twice daily [day, night]
SO_2 Concentration (following large volcanic eruptions)	2	Global, 10–30 km	200 km horizontal resolution, ~3 km vertical resolution/ twice daily [day, night]
OMI *Data Set Start Date: August 17, 2004*			
Radiances	1B	Global	13 km × 24 km horizontal resolution/daily
Total Ozone	2	Global—total atmospheric column	13 km × 24 km horizontal resolution/daily
Ozone Profile	2	Global, for altitudes of 15–45 km	13 km × 48 km horizontal resolution, 6 km vertical resolution/daily
Surface UVB flux	2	Global—Earth's surface	13 km × 24 km horizontal resolution/daily
Cloud Scattering Layer Pressure	2	Global	13 km × 24 km horizontal resolution/daily
Aerosol Optical Thickness	2	Global—total atmospheric column	13 km × 24 km horizontal resolution/daily
Aerosol Single Scatterer Albedo	2	Global	13 km × 24 km horizontal resolution/daily
SO_2	2	Global—total atmospheric column	13 km × 24 km horizontal resolution/daily

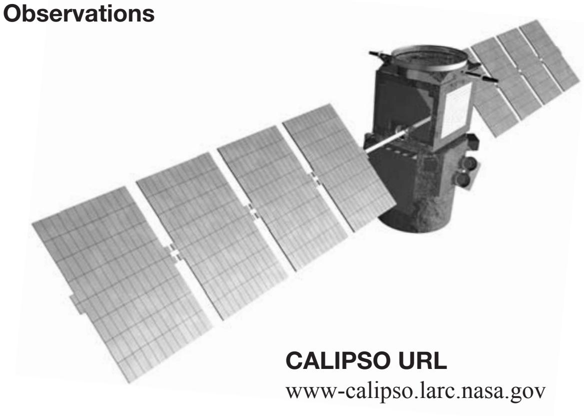
Aura Data Products

Product Name or Grouping	Processing Level	Coverage	Spatial/Temporal Characteristics
NO_2	2	Global—total atmospheric column and tropospheric column	13 km × 24 km horizontal resolution/daily
HCHO	2	Global—total atmospheric column	13 km × 24 km horizontal resolution/daily
BrO	2	Global—total atmospheric column	13 km × 24 km horizontal resolution/daily
OClO	2	Antarctic Polar Vortex region—slant column	13 km × 24 km horizontal resolution/daily
TES *Data Set Start Date: August 22, 2004*			
Level 1B Radiance, (IR spectra in selected bands 3.2–15.4 µm)	1B	Global	5.3 km × 8.3 km horizontal resolution/ every 16 days (compiled over alternate days)
CH_4 Mixing Ratio	2	Global for altitudes of 0–34 km	5.3 km × 8.3 km horizontal resolution, 2–6 km vertical resolution/every 16 days (compiled over alternate days)
CO Mixing Ratio	2	Global, 0–34 km	5.3 km × 8.3 km horizontal resolution, 2–6 km vertical resolution/every 16 days (compiled over alternate days)
HNO_3 Mixing Ratio	2	Global, 0–34 km	5.3 km × 8.3 km horizontal resolution, 2–6 km vertical resolution/every 16 days (compiled alternate days)
NO_2 Mixing Ratio	2	Global, 0–34 km	5.3 km × 8.3 km horizontal resolution, 2–6 km vertical resolution/every 16 days (compiled over alternate days)
O_3 Mixing Ratio	2	Global, 0–34 km	5.3 km × 8.3 km horizontal resolution, 2–6 km vertical resolution/every 16 days (compiled over alternate days)
H_2O Mixing Ratio	2	Global, 0–34 km	5.3 km × 8.3 km horizontal resolution, 2–6 km vertical resolution/every 16 days (compiled over alternate days)
Temperature Profile	2	Global, 0–34 km	5.3 km × 8.3 km horizontal resolution, 2–6 km vertical resolution/every 16 days (compiled over alternate days)
Land–Surface Temperature	2	Global, 0–34 km	5.3 km × 8.3 km horizontal resolution, 2–6 km vertical resolution/every 16 days (compiled over alternate days)

Aura Data Products

CALIPSO

Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations



CALIPSO URL
www-calipso.larc.nasa.gov

Summary

CALIPSO is a joint U.S. (NASA)/French (Centre National d'Etudes Spatiales/CNES) mission. Observations from spaceborne lidar, combined with passive imagery, will lead to improved understanding of the role aerosols and clouds play in regulating the Earth's climate, in particular, how aerosols and clouds interact with one another.

Key CALIPSO Facts

Joint with France

Spacecraft: PROTEUS

Orbit:
- Type: Sun-synchronous
- Altitude: 705 km
- Inclination: 98.2°
- Period: 99 minutes
- Repeat Cycle: 16 days

Dimensions: 1.49 m × 1.84 m × 2.31 m

Mass: 600 kg

Power: 562 W

Design Life: 3 years

Average Data Rate: 34 Gb/day

Downlink: S-band@600 kbps, Kiruna; X-band@20 Mbps, North Pole, Alaska

Platform Pointing Requirements (3σ):
- Control: 0.05°
- Knowledge: 0.04°

Design Life: 3 years.

Contributors: CNES, Alcatel

Instruments

- Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP)
- Imaging Infrared Radiometer (IIR)
- Wide-Field Camera (WFC)

Points of Contact

- *Principal Investigator:* Dave Winker, NASA Langley Research Center
- *French Co-Principal Investigator:* Jacques Pelon, l'Institut Pierre Simon Laplace
- *U.S. Co-Principal Investigator:* Pat McCormick, Hampton University

Other Key Personnel

- *Program Scientist:* Donald Anderson, NASA Headquarters
- *Program Executive:* Steve Volz, NASA Headquarters
- *Mission Manager:* Bryant Cramer, NASA Goddard Space Flight Center
- *Project Manager:* Dale Schulz, NASA Goddard Space Flight Center

Mission Type

Earth Observing System (EOS) Exploratory Mission (Earth System Science Pathfinder)

Launch

- *Date and Location:* April 28, 2006 (shared launch with CloudSat), from Vandenberg Air Force Base, California
- *Vehicle:* Delta II rocket

Relevant Science Focus Areas

(see NASA's Earth Science Program section)

- Atmospheric Composition
- Climate Variability and Change
- Water and the Energy Cycles
- Weather

Related Applications

(see Applied Sciences Program section)

- Air Quality
- Aviation
- Homeland Security
- Public Health

CALIPSO Mission Background

Aerosols affect the Earth's radiation budget through the scattering and absorption of incoming sunlight, which acts as a significant radiative forcing. Aerosols are also intimately linked to the formation of clouds and to precipitation processes and thus to the hydrologic cycle. It now appears likely that aerosols resulting from human activities such as the use of fossil fuels and agricultural burning are affecting global climate. Aerosols also affect public health in heavily polluted regions. Unlike greenhouse gases, tropospheric aerosols are highly variable in space and time due to variable sources and short atmospheric residence times. Because of this variability and the difficulty of monitoring aerosols using satellite instruments, basic questions remain on the global distribution and properties of aerosols. Model estimates of the radiative forcing from aerosols are still uncertain, and improved capabilities to observe aerosols from space are required to constrain key assumptions in these models.

The sensitivity of the climate response to radiative forcings from aerosols, greenhouse gases, and other sources is largely controlled by the interactions between clouds and radiation. Advances in modeling capabilities to predict climate change require improved representations of cloud processes in models and decreased uncertainties in parameterizations of cloud-radiation interactions. In particular, the largest sources of uncertainty in estimating longwave radiative fluxes at the Earth's surface and within the atmosphere are connected with current difficulties in determining the vertical distribution and overlap of multi-layer clouds and the ice-water path of these clouds. The CALIPSO mission will provide unique profile measurements to improve our understanding of the role of aerosols and clouds in the Earth's climate system. CALIPSO will enhance current capabilities by providing: global, vertically-resolved measurements of aerosol and cloud distributions; height-resolved discrimination of aerosols into several types; and observations of aerosols over bright and heterogeneous surfaces both day and night. CALIPSO will also provide vertically-resolved identification of cloud ice/water phase and, together with the cloud profiling radar on CloudSat, will provide comprehensive observations of cloud vertical structure on a global scale. CALIPSO will fly as part of the A-Train of satellites including four other NASA missions—Aqua, Aura, CloudSat, and Orbiting Carbon Observatory (OCO)—as well as a CNES mission called Polarization and Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar (PARASOL). This combination of observations offers an unprecedented resource for exploring aerosol-chemistry-cloud interactions.

The CALIPSO payload consists of three nadir-viewing instruments: the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP–pronounced 'caliope') and two passive instruments, the Imaging Infrared Radiometer (IIR) and the Wide-Field Camera (WFC).

Key CALIOP Facts

Heritage: Lidar In-space Technology Experiment (LITE), military laser rangefinders

Instrument Type: Nadir-pointing dual-wavelength polarization lidar

Wavelengths: 532 nm (polarization-sensitive) and 1064 nm

Science Operations Mode:
Pulse Rate: 20 Hz
Vertical sampling: 30 m, 0–40 km
Footprint spacing: 333 m along-track
Duty Cycle: 100%

Repeat Cycle: 16 days

Dimensions: 1 m × 1.49 m × 1.31 m
Sensor Unit: 1 m (dia) × 1.31 m
Control Unit: 30 cm × 30 cm × 25 cm

Technical Resource Allocations:
Mass: 156 kg
Power: 207 W
Data Rate: 332 kbps

Performance:
Pulse Power: 110 mJ
Pulse Length: 20 ns
Footprint Diameter: 70 m
Calibration: 5% (532 nm)
Linear Dynamic Range: 4×10^6 : 1

Thermal Control: Provided by heaters and passive radiators

Contributor: Ball Aerospace & Technologies Corp.

Key IIR Facts

Heritage: IASI Infrared Sensor Module

Instrument Type: Imaging spectroradiometer

Scan Type: Earth imaging, nadir pointing

Calibration: Onboard black body source, deep space view

Field of View (FOV): 64 km

Instrument IFOV: 1 km

Transmission Rate: N/A

Swath: 64 km

Spatial Resolution: 1 km, 64 × 64 pixels

Spectral Range: 3 channels centered at 8.65, 10.6, and 12.05 µm

Dimensions: 490 mm × 550 mm × 320 mm

CALIOP

Cloud-Aerosol Lidar with Orthogonal Polarization

Two-wavelength, polarization lidar capable of providing aerosol and cloud profiles and properties.

CALIOP provides information on the vertical distribution of aerosols and clouds and their optical and physical properties. CALIOP will improve not only our understanding of aerosols and clouds, but also our understanding of aerosol-cloud interactions. CALIOP is built around a diode-pumped Nd:YAG laser producing linearly-polarized pulses of light at 1064 nm and 532 nm. The atmospheric return is collected by a 1-m telescope, which feeds a three-channel receiver measuring the backscattered intensity at 1064 nm and the two orthogonal polarization components at 532 nm (parallel and perpendicular to the polarization plane of the transmitted beam). Two-wavelength polarization measurements provide information on aerosol size and hydration. Lidar polarization measurements also allow discrimination of cloud ice/water phase. Data from CALIOP will be combined with data from the other CALIPSO instruments (IIR and WFC), to retrieve cirrus emissivity and particle size. Information on radiative fluxes will be provided by combining CALIOP profile measurements with TOA fluxes from CERES and multi-spectral observations from Aqua's MODIS. CALIOP and the Cloud Profiling Radar on CloudSat have complementary cloud sensing capabilities that allow the production of a comprehensive combined cloud profile product.

IIR

Imaging Infrared Radiometer

Three-channel infrared imager that complements CALIOP and provides additional cloud properties.

The IIR provides calibrated radiances at 8.65, 10.6, and 12.05 μm over a 64 km swath centered on the lidar footprint. These wavelengths are chosen to optimize combined lidar/IIR/WFC retrievals of cirrus emissivity and particle size. The IIR is built around an Infrared Sensor Module developed for the IASI instrument. Use of a microbolometer-detector array in a non-scanning, staring configuration allows a simple and compact design to perform measurements at a 1-km resolution with a NEΔT better than 0.3 K (at 210 K) in all spectral bands. The IIR instrument is provided by CNES with algorithm development performed by the Institute Pierre Simon Laplace (Paris).

WFC

Wide-Field Camera

Single-channel, nadir-viewing, push-broom, visible imager that, when combined with IIR data, provides meteorological context around the lidar footprint.

The WFC is a modified star tracker camera, with a single channel covering the 620–670-nm spectral region, providing images of a 61-km swath with a spatial resolution of 125 m. The WFC provides meteorological context for the lidar measurements and allows highly accurate

Key IIR Facts *(cont.)*

Mass: 21 kg

Power: 26.6 W

Duty Cycle: 8.184 s

Data Rate: 48.2 kbps

Contributors: CNES, SODERN (Paris)

Key WFC Facts

Heritage: Star tracker cameras

Radiometric Response Stability: < 1% over 24 hours

Duty Cycle: 39% (Daylight portions of orbit with solar zenith angle (SZA) < 70°)

Data Rate: 16.1 kbps

FOV: 61-km cross-track × 125-m along-track

Incidence Angle: Nadir

Instrument IFOV: 125 m × 125 m

Dimensions: 14 cm diameter × 24 cm sensor unit

Mass: 2.6 kg

Power: 7.9 W

Thermal Control: TEC and passive radiator

Thermal Operating Range: CCD operates at 0° C

Sampling Interval: 18.5 ms

Spatial Resolution:
- Central high-resolution swath (within 2.5 km of lidar footprint): 125 m × 125 m
- Low-resolution swath (28 km either side of high res. swath): 1 km × 1 km

Wavelength: 645 nm

Spectral Resolution: 50 nm

Contributor: BATC

spatial registration, when required, between CALIPSO and instruments on other satellites of the A-Train afternoon constellation. WFC data are also used in daytime retrievals of cloud properties.

CALIPSO References

Winker, D. M., J. Pelon, and M. P. McCormick, 2002: The CALIPSO Mission: Spaceborne lidar for observation of aerosols and clouds. *Proc. SPIE*, **4893**, 1–11.

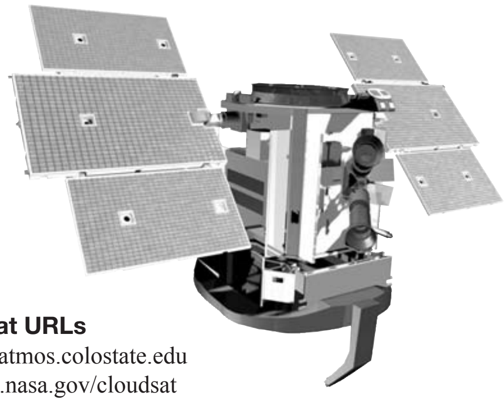
Winker, D. M., W. H. Hunt, and C. A. Hostetler, 2004: Status and performance of the CALIOP Lidar. *Proc. SPIE*, **5575**, 8–15.

CALIPSO Data Products

Product Name or Grouping	Processing Level	Coverage	Spatial/Temporal Characteristics
CALIOP			
Attenuated Backscatter Profiles	1B	Global, for altitudes of -0.5–40 km	-0.5–8.2 km altitudes: 0.33 km horizontal resolution (hres), 30 m vertical resolution (vres); 8.2–20.2 km altitudes: 1.00 km hres, 60 m vres; 20.2–30.1 km altitudes: 1.67 km hres, 180 m vres; 30.1–40 km altitudes: 5 km hres, 300 m vres/ every 16 days
Aerosol Layer Heights	2	Global	0–30.1 km altitudes: 5 km hres; 30–180 m vres/ every 16 days
Aerosol Backscatter Profiles	2	Global, 0–30.1 km	0–20.2 km altitudes: 40 km hres, 120 m vres; 20.2–30.1 km altitudes: 40 km hres, 360 m vres/ every 16 days
Aerosol Extinction Profiles	2	Global, 0–30.1 km	0–20.2 km altitudes: 40 km hres, 120 m vres; 20.2–30.1 km altitudes: 40 km hres, 360 m vres/ every 16 days
Cloud Top and Base Heights	2	Global, 0–20.2 km	0.33 km hres, 1 km hres, and 5 km hres; 30–60 m vres/every 16 days
Cloud Extinction Profiles	2	Global, 0–20.2 km	5 km hres, 60 m vres/ every 16 days
Cloud Ice / Water Phase	2	Global, 0–20.2 km	1 km hres, 30-60 m vres/ every 16 days
IIR			
Infrared Radiances	1B	Global	1 km hres/every 16 days
WFC			
Visible Reflectances	1B	Global	0.125 km hres and 1 km hres/ every 16 days
CALIOP/IIR/WFC			
Cloud Emissivity	2	Global	1 km hres/every 16 days
Cloud Particle Size	2	Global	1 km hres/every 16 days
Surface Radiative Fluxes (with CERES from Aqua)	4	Global	30 km hres/every 16 days
Atmospheric Radiative Flux Profiles (with CERES from Aqua)	4	Global, TOA to surface	30 km hres; 18 vertical levels/every 16 days

CALIPSO Data Products

CloudSat



CloudSat URLs
cloudsat.atmos.colostate.edu
essp.gsfc.nasa.gov/cloudsat
cloudsat.cira.colostate.edu

Summary

CloudSat will study clouds in detail to better characterize the role they play in regulating Earth's climate. CloudSat will provide the first direct, global survey of the vertical structure and overlap of cloud systems and their liquid- and ice-water contents. Data returned should lead to improved cloud representations in atmospheric models, which should help improve the accuracy of weather forecasts and climate predictions made using these models.

Instrument

Cloud Profiling Radar (CPR)

Points of Contact

- *CloudSat Principal Investigator:* Graeme Stephens, Colorado State University
- *CloudSat Deputy Principal Investigator:* Deborah Vane, NASA Jet Propulsion Laboratory/California Institute of Technology

Other Key Personnel

- *CloudSat Program Scientist:* Donald Anderson, NASA Headquarters
- *CloudSat Program Executive:* Steve Volz, NASA Headquarters
- *CloudSat Project Manager:* Thomas Livermore, NASA Jet Propulsion Laboratory/California Institute of Technology

Mission Type

Earth Observing System (EOS) Exploratory Mission (Earth System Science Pathfinder)

Key CloudSat Facts

Joint with Canada

Orbit:
Type: Sun-synchronous
Altitude: 705 km
Inclination: 98.2°
Period: 99 minutes
Repeat Cycle: 16 days

Dimensions: 2.3 m × 2.3 m × 2.8 m

Mass: 999 kg

Power: 700 W

Downlink: S-band to U.S. Air Force antenna network

Mission Life: 22 months

Design Life: 3 years

Contributors

Canadian Space Agency (CSA), U.S. Air Force (USAF), U.S. Department of Energy (DOE)

Launch

Date and Location: April 28, 2006 (shared launch with CALIPSO), from Vandenberg Air Force Base, California

Vehicle: Delta II rocket

Relevant Science Focus Areas

(see NASA's Earth Science Program section)

- Climate Variability and Change
- Weather

Related Applications

(see Applied Sciences Program section)

- Aviation

Also valuable for weather prediction

CloudSat Science Goals

Profile the vertical structure of clouds: Understanding the vertical structure of clouds is fundamentally important to improving our understanding of how clouds affect both the local and large-scale environment.

Measure the profiles of cloud liquid water and ice water content: These two quantities—predicted by cloud process and global scale models alike—determine practically all other cloud properties, including precipitation and cloud optical properties.

Measure profiles of cloud optical properties: These measurements, when combined with water and ice content information, provide critical tests of key cloud process parameterizations and enable the estimation of flux profiles and radiative heating rates through the atmospheric column.

CloudSat Mission Background

Clouds and their properties are inadequately represented in climate models, leading to continued uncertainty in the prediction of global warming with increasing carbon dioxide (CO_2). Even small changes in abundance or distribution of clouds can profoundly alter the climate response to changes in greenhouse gases. Clouds also influence climate by affecting the efficiency at which the hydrological cycle operates.

One of the main reasons model predictions of climate warming vary from model to model is the different ways models specify vertical cloud distributions and overlap. The vertical distribution and overlap of cloud layers directly determine both the magnitude and vertical profile of heating in the atmosphere. The heating by high cloud layers in the tropical atmosphere exerts a dominant influence on the large-scale, 'Hadley' circulation of the atmosphere. The vertical distribution of clouds assumed in models also influences the predicted precipitation. Direct measurements of the vertical structure of clouds have, until now, been limited to a few ground-based sites.

CloudSat will provide the observations necessary to advance our understanding of these issues. It will provide the first direct measurements of cloud vertical structure on a global basis. CloudSat will also measure the profiles of cloud liquid-water and ice-water content (microphysical properties) and will match these microphysical properties to cloud optical properties. This matching is a critical test of key parameterizations in models that enable calculation of flux profiles and radiative heating rates throughout the atmosphere.

CloudSat data will provide a rich source of information for evaluating cloud properties derived from other satellite data. CloudSat will fly as part of the A-Train of satellites including four other NASA missions—Aqua, Aura, Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO), and eventually the Orbiting Carbon Observatory (OCO)—as well as a French Centre National d'Etudes Spatiales (CNES) mission called Polarization and Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar (PARASOL). This combination of observations offers an unprecedented resource for exploring aerosol-chemistry-cloud interactions.

CPR

Cloud Profiling Radar

CPR is a 94-GHz radar with 500-m vertical resolution. The radar sends out a pulse and receives a return signal. Because the 94-GHz signal is not strongly attenuated by most clouds, the radar should be able to detect more than 90% of all ice clouds and 80% of all water clouds.

CloudSat will utilize a 94-GHz Cloud Profiling Radar to obtain measurements of cloud properties. Cloud radars now operate routinely or quasi-routinely at a number of surface sites worldwide and are also deployed on a number of research aircraft. Measurements collected by these instruments provide a rich heritage for the CloudSat radar.

Because clouds are weak scatterers of microwave radiation, the overriding requirement on the radar is to achieve the maximum possible sensitivity and hence maximize cloud detection. Sensitivity is primarily determined by radar-received power and noise level, and optimizing this sensitivity involves a careful tradeoff among competing and conflicting factors, including the cloud backscattering properties, the vertical resolution, atmospheric attenuation, available power delivered to the system, the orbit altitude, and radar technology. Increasing the antenna size and increasing transmitter output power are both ways to increase the power received. The antenna diameter of 1.85 m is limited by launch constraints. The transmitter power is also limited by both the transmitter technology and the power-supply capability of the spacecraft.

The amount of power received is also strongly influenced by the cloud reflectivity and atmospheric attenuation. Cloud reflectivity increases with increasing radar frequency but atmospheric attenuation becomes prohibitive at higher frequencies. From these considerations, the operating frequency of 94 GHz is an optimum compromise and provides an increase of more than 30 dB over the 14-GHz Tropical Rainfall Measuring Mission (TRMM) radar. An international frequency allocation of 94 GHz has been established for spaceborne radar use.

Sensitivity is also related to the pulse length. The radar uses 3.3-μs pulses providing cloud and precipitation information with a 500-m vertical range resolution between the surface and 25 km. The radar measurements along-track are averaged by the on-board data processor over 0.16 s intervals, producing an oblong effective footprint of 1.4 km × 1.8 km. The radar data can be further averaged in ground processing to 0.48 s, increasing the effective footprint in the along-track dimension to 3.8 km. This provides the averaging needed to achieve the required sensitivity.

CPR will be sensitive enough to detect the majority of clouds that significantly affect the radiation budget and critical elements of the water budget of the atmosphere. CPR is expected to detect 90% of all ice clouds and 80%

of all water clouds. Other sensors that are flying or will fly as part of the A-Train formation, particularly the Moderate Resolution Imaging Spectroradiometer (MODIS) on Aqua and the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) on CALIPSO, are expected to augment the cloud-detection capabilities of CPR. Likewise, CPR will improve the cloud-detection capabilities of MODIS. This is but one of many examples of the value of the synergistic measurements enabled by the A-Train formation.

If CloudSat were flying in isolation, it would probably reside at a lower altitude, similar to that of TRMM. This would give CPR even greater sensitivity and improved ability to detect clouds. However, because CloudSat has chosen to be part of the A-Train formation, it flies at a higher altitude. This compromise still gives CPR excellent cloud-detection capabilities to achieve CloudSat's mission objectives, while also enabling maximum synergism with the other A-Train missions.

The antenna subsystem consists of the collimating antenna and the Quasi-Optical Transmission Line (QOTL). The antenna, constructed of composite graphite material, meets the challenge of low surface roughness (less than an RMS of 0.05 mm over the entire surface) and delivers a highly directional beam of half-width less than 12°. The antenna also has the far-side lobe levels 50 dB below that of the main lobe, as required to remove aliasing of these side lobes into the profiles of following pulses. The QOTL minimizes loss through the system. This will be the first time QOTL technology has flown in space at the wavelength of this radar. Another important challenge in the radar design is the High Power Amplifier (HPA) subsystem. The HPA has complete redundancy and consists of two Extended Interaction Klystrons (EIKs) and two high-voltage power supplies. One key development was the redesign of the commercial EIK unit to become qualified to operate in space.

CPR URL

cloudsat.atmos.colostate.edu

CloudSat References

Stephens, G. L., D. G. Vane, R. J. Boain, G. G. Mace, K. Sassen, Z. Wang, A. J. Illingworth, E. J. O'Connor, W. B. Rossow, S. L. Durden, S. D. Miller, R. T Austin, A. Benedetti, C. Mitrescu, and the CloudSat Science Team, 2002: The CloudSat Mission and the A-Train: A new dimension of space based observations of clouds and precipitation. *Bull. Amer. Meteor. Soc.*, **83**, 1771–1790.

Key CPR Facts

Heritage: Aircraft and ground-based 94-GHz radars

Nadir-pointing 94-GHz radar measures cloud reflectivity vs. altitude along nadir track

Single science operation mode
- Vertical resolution: ~500 m from 0 to 25 km altitude
- Transmits 3.3-μs monochromatic pulses
- Horizontal resolution: ~1.4 km
- Duty cycle: 100%

Technical Resource Allocations:
- Mass: 260 kg
- Power: 270 W

Data Rate: 25 kbps

Antenna: 1.85-m diameter

Performance:
- Minimum detectable reflectivity: -26 dBZ, nominally –28 dBZ
- W-band frequency: 94 GHz
- High radiated power: > 1.5 kW
- High-gain antenna: 62 dBi
- Low sidelobes: -50 dB
- Quasi-optical (free space) front end to minimize RF loss
- Noise subtraction to measure signals that are ~15 dB below noise floor

Calibration: 1.5 dB

Dynamic Range: 80 dB to capture low-reflectivity clouds and surface return

Platform Pointing Requirements (platform + instrument, 3σ):
- Control: < 0.1°
- Knowledge: < 0.1°

Spacecraft Design: Ball Aerospace

Instrument Design: NASA JPL, Canadian Space Agency

Data Processing: Cooperative Institute for Research in the Atmosphere (CIRA) (Colorado State University)

Ground Operations: U.S. Air Force

Validation: DOE, Atmospheric Radiation Measurements (ARM) Program and the contributions of many Co-I institutions and facilities around the world.

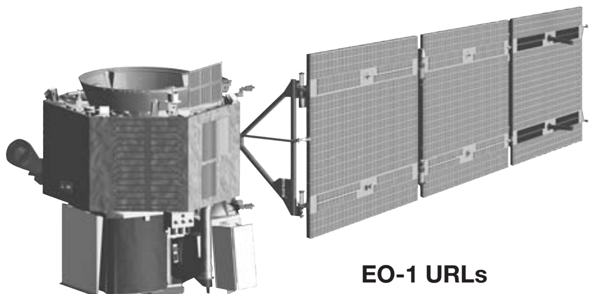
CloudSat Data Products

Product Name or Grouping	Processing Level	Coverage	Spatial/Temporal Characteristics
CPR			
Raw CPR Data	0	Global, along nadir track	500 m vertical resolution/ twice daily [day, night]
Auxiliary Data	1A	Global, along nadir track	500 m vertical resolution/ twice daily [day, night]
Calibrated Radar Reflectivities	1B	Global, along nadir track	500 m vertical resolution/ twice daily [day, night]
Cloud Geometric Profile—expressed in terms of occurrence and reflectivity (significant echoes); includes (gas) attenuation corrections	2B	Global, along nadir track	500 m vertical resolution/ twice daily [day, night]
Classification of Cloud Type, Including Precipitation Identification and Likelihood of Mixed-Phase Conditions	2B	Global, along nadir track	500 m vertical resolution/ twice daily [day, night]
Cloud Optical Depth (by layer)	2B	Global, along nadir track	500 m vertical resolution/ twice daily [day, night]
Cloud Liquid-Water Content	2B	Global, along nadir track	500 m vertical resolution/ twice daily [day, night]
Cloud Ice-Water Content	2B	Global, along nadir track	500 m vertical resolution/ twice daily [day, night]
Atmospheric Radiative Fluxes and Heating Rates	2B	Global, along nadir track	500 m vertical resolution/ twice daily [day, night]

CloudSat Data Products

EO-1

Earth Observing-1



EO-1 URLs
eo1.usgs.gov/
eo1.gsfc.nasa.gov/

Key EO-1 Facts

Orbit:
Type: Sun-synchronous
Equatorial Crossing: 10:01 a.m.
Altitude: 705 km
Inclination: 98.2°
Period: 98.8 minutes
Repeat Cycle: 16 days

Dimensions: 2 m height × 2.5 m diameter

Mass: 529 kg

Power: 300 W

Design Life: 18 months; EO-1 is well beyond its planned mission life and is still functioning

Downlink: X-Band (105 Mbps), Sioux Falls, Svalbard, Alaska, Hobart (Australia)

Note: Part of the Morning Constellation of satellites, lags one minute behind Landsat 7

Contributors

ALI: MIT/Lincoln Laboratory, NASA GSFC
Hyperion: TRW, NASA GSFC
LAC: NASA GSFC Applied Engineering and Technology Directorate (AETD)

Summary

EO-1 is a one-year technology validation / demonstration mission designed to demonstrate new technologies and strategies for improved Earth observations. The satellite contains three observing instruments supported by a variety of newly developed space technologies.

Instruments

- Advanced Land Imager (ALI)
- Hyperspectral Instrument (Hyperion)
- Linear Etalon Imaging Spectral Array (LEISA) Atmospheric Corrector (LAC)

Points of Contact

EO-1 Project Scientist: Stephen G. Ungar, NASA Goddard Space Flight Center

Other Key Personnel

EO-1 Program Scientist: Garik Gutman, NASA Headquarters

EO-1 Mission Director: Dan Mandl, NASA Goddard Space Flight Center

Mission Type

Earth Observing System (EOS) Technology Demo (New Millennium Program)

Launch

Date and Location: November 21, 2000, from Vandenberg Air Force Base, California

Relevant Science Focus Areas

(see NASA's Earth Science Program section)

- Carbon Cycle, Ecosystems, and Biogeochemistry
- Earth Surface and Interior

Related Applications

(see Applied Sciences Program section)

- Agricultural Efficiency
- Air Quality
- Aviation
- Carbon Management
- Coastal Management
- Energy Management
- Homeland Security
- Public Health
- Water Management

EO-1 Mission Goals

- Validate and test new technologies that could provide significant cost reductions and improved performance for future Landsat missions.

- Provide a science-grade space-borne hyperspectral instrument, thus providing a new class of Earth observation data for improved Earth surface characterization.

- Provide the first space-based test of an onboard atmospheric corrector for increasing the accuracy of surface reflectance estimates.

EO-1 Extended Mission Goals

- Sustain and enhance U.S. Geological Survey (USGS) and NASA research and development toward applications of hyperspectral and pushbroom multispectral data within the U.S. research and operational user communities.

- Promote opportunities within the remote sensing community to apply evolving imaging technology for government, scientific, and industry applications.

- Provide greater insight into potential commercial developers' prototype instrument performance.

- Add unique land remote sensing datasets to the USGS National Satellite Land Remote Sensing Data Archive.

- Characterize long-term performance of the EO-1 advanced technology sensors.

EO-1 Mission Background

EO-1 was developed as part of NASA's New Millennium Program (NMP) to demonstrate new technologies and strategies for improved Earth observations. The EO-1 satellite contains three observing instruments supported by a variety of newly developed space technologies. Instrument performances are validated and carefully monitored through a combination of radiometric calibration approaches: solar, lunar, stellar, Earth (vicarious) and atmospheric observations complemented by onboard calibration lamps and extensive pre-launch calibration. Techniques for spectral calibration of space-based sensors have been tested and validated with Hyperion. ALI and Hyperion instrument performances continue to meet or exceed predictions well beyond the planned one-year program.

The original EO-1 mission was successfully completed in November 2001. All data from the first year are currently available through the USGS Earth Resources Observation System (EROS) Data Center (EDC). As the end of the mission approached, the remote-sensing research and scientific communities expressed high interest in continued acquisition of image data from EO-1. Based on this user interest, NASA and USGS reached an agreement to allow continuation of the EO-1 Program as an Extended Mission.

The Extended Mission began in February of 2002 with the transfer of acquisition planning and scheduling, as well as data processing and distribution responsibilities, to EDC. As of early 2006, EO-1 is still fully functional and acquiring in excess of

Key ALI Facts

Heritage: ETM+ (Landsat 7)

Instrument Type: Linear Multi-Spectral Array

Scan Type: Pushbroom Sequential Sampling

Calibration: Pre-launch with on-orbit validation (solar, lunar, stellar, and vicarious)

Field of View (FOV): 3°

Instrument IFOV: 0.043 mrad (Multi-Spectral [MS]), 0.014 mrad (Panchromatic [Pan])

Transmission Rate: N/A

Swath: 37 km × 42 km (standard length), length can be adjusted

Spatial Resolution: 30 m (MS), 10 m (Pan)

Spectral Range: 0.43–2.3 µm

Dimensions: 0.9 m × 0.9 m × 0.7 m

Mass: 90 kg

Power: 100 W

Duty Cycle: Continuous (Data capacity limited by onboard storage)

Data Rate: 55 Mbps

Key Hyperion Facts

Heritage: Lewis Hyperspectral Imager (HSI)

Instrument Type: Grating Imaging Spectrometer Array

Scan Type: Pushbroom Simultaneous Sampling

Calibration: Pre-launch with on-orbit validation (solar, lunar, stellar, and vicarious)

FOV: 0.63°

Instrument IFOV: 0.043 mrad

Transmission Rate: N/A

Swath: 7.7 km × 42 km (standard length), length can be adjusted

Spatial Resolution: 30 m

120 scenes per week. All EO-1 data orders and tasking requests may be placed directly through the EDC website at eo1.usgs.gov. The EO-1 Extended Mission is chartered to collect and distribute Advanced Land Imager (ALI) multispectral and Hyperion hyperspectral products in response to Data Acquisition Requests (DARs). Under the Extended Mission provisions, image data acquired by EO-1 are archived and distributed by EDC and placed in the public domain.

EO-1 is part of the morning constellation of satellites, which also includes Terra, Landsat 7, and Satelite de Aplicaciones Cientificas-C (SAC-C). The EO-1 spacecraft follows Landsat 7 by approximately one minute. It is capable of cross-track pointing to allow potential imaging within one full adjacent Worldwide Reference System (WRS) path in each direction from the current flight path. Each ALI scene covers approximately one-fifth the width of a Landsat 7 Enhanced Thematic Mapper Plus (ETM+) scene. Hyperion scenes are acquired in strips, with a cross-track width of 7.7 km. Imagery from either sensor will have a user-specified along-track length of either 42 km or 185 km (equivalent to one full Landsat 7 ETM+ scene length).

Validating Revolutionary Spacecraft Technologies

The future of Earth science measurements requires that spacecraft have ever greater capabilities packaged in more-compact and lower-cost spacecraft. To this end, EO-1 tests five new technologies that will enable new or more cost-effective approaches to conducting science missions in the 21st century. These are: the X-band Phased Array Antenna, used for downlinking data gathered by the EO-1 science instruments; Enhanced Formation Flying, an autonomous, onboard, relative navigation and formation-flying control; the Pulsed Plasma Thruster, used for fine-attitude precision control; the Lightweight Flexible Solar Array, an advanced photo-voltaic solar array that utilizes a lightweight solar blanket and a shockless, shaped-hinge-deployment mechanism to achieve two-to-three times the specific power over conventional solar arrays; and the Carbon-Carbon Radiator, which has superior thermal radiating properties over conventional materials.

Other EO-1 Technology Challenges

The EO-1 imaging instruments presented a significant challenge to traditional spacecraft development. Because of EO-1's high-rate imaging (almost 1 gigabit per second (Gbps) when all three instruments are on), a specific subsystem on the EO-1 observatory needed to be designed and crafted to handle the data rate while still maintaining flight constraints of compact size and low power usage.

Although not officially part of the NMP/EO-1 validation list, the Wideband Advanced Recorder Processor (WARP) is a solid-state recorder with capability to record data from all three instruments simultaneously and store up to 48 Gbits (2–3 scenes) of data before transmission to the ground. WARP's compact design, advanced solid-state memory devices (3-dimensional RAM stacks) and packaging techniques enable EO-1 to collect and downlink all recorded data.

Key Hyperion Facts *(cont.)*

Spectral Range: 0.43–2.5 µm

Dimensions: 0.39 m × 0.75 m × 0.66 m

Mass: 49 kg

Power: 51 W

Duty Cycle: Approximately 50% (maximum power-on duration 50 minutes)

Data Rate: 221 Mbps

Key LAC Facts

Heritage: Lewis Atmospheric Corrector

Instrument Type: Linear Etalon Imaging Spectral Array

Scan Type: Pushbroom Sequential

Calibration: On-Orbit

FOV: 15°

Instrument IFOV: 0.354 mrad

Transmission Rate: N/A

Swath: 185 km × 195 km

Spatial Resolution: 250 km

Spectral Range: 0.9–1.6 µm

Dimensions:

Electronics Module: 25 cm × 23 cm × 18 cm

Optics Module: 19 cm × 18 cm × 14 cm

Mass: 10.5 kg

Power: 15 W (48 W peak), < 15 W orbit average

Duty Cycle: Approximately 50% (maximum power-on duration 24 minutes)

Data Rate: 189 Mbps

Instrument Descriptions

The three remote-sensing instruments on the EO-1 observatory are the Advanced Land Imager (ALI), the Hyperion Imaging Spectrometer (Hyperion) and the Linear Etalon Imaging Spectral Array (LEISA) Atmospheric Corrector (LAC). All three instruments employ a pushbroom data-acquisition method and operate within the 0.4–2.5-µm spectral range.

ALI

Advanced Land Imager

The ALI instrument is a multi-spectral pushbroom radiometer designed to test concepts for Landsat follow-on missions.

ALI features 10-m ground resolution in the panchromatic (black and white) band, and 30-m ground resolution in its nine other multispectral bands. ALI uses a four-chip multispectral focal-plane array that covers seven of the eight bands of the current Landsat imagers. The swath width of ALI is 37 km. The Massachusetts Institute of Technology/Lincoln Laboratory (MIT/LL) developed ALI under project management from NASA GSFC, Greenbelt, Maryland. MIT/LL provides open access to U.S. industry regarding the design and performance of ALI with the explicit purpose of expediting technology transfer to the commercial sector.

Hyperion

Hyperspectral Imager

Hyperion scans the Earth through 220 different spectral channels and demonstrates hyperspectral imaging techniques that can be used to classify complex land ecosystems based on their spectral signature.

Hyperion provides a class of Earth observation data leading to improved surface spectral characterization. Hyperion capabilities provide resolution of surface properties into hundreds of spectral bands. Through 220 channels, Hyperion demonstrates the ability to perform detailed spectral mapping with high radiometric accuracy. In the future, an operational version of Hyperion will allow complex land ecosystems to be imaged and accurately classified. The swath width of Hyperion is 7.7 km and is aligned to view some of the same ground, at the same spatial resolution (30 m) as ALI, to aid in cross-comparisons between these instruments. Hyperion was developed by TRW, Redondo Beach, California, under project management from NASA GSFC.

LAC

Linear Etalon Imaging Spectral Array (LEISA) Atmospheric Corrector

LAC is a wedge imaging spectrometer that can be used to remove the effects of the atmosphere from surface pictures, thus improving imagery and hyperspectral-sensing capabilities.

LAC is an infrared camera. Images from LAC can be used to remove the effects of the atmosphere from surface pictures obtained by instruments such as ALI on EO-1 and ETM+ on Landsat. Observing the surface through the atmosphere is conceptually the same as viewing the bottom of a lake through cloudy water. LAC provides data on the amount of atmospheric water vapor. These data can be used to clear the view. LAC on EO-1 will be the first use of a dedicated instrument to perform this function on a real-time basis. This instrument will provide scientific return both in terms of improved imagery and hyperspectral sensing capabilities. It will also test a number of new technologies. Because LAC is small and adaptable to different spacecraft configurations, it is a bolt-on instrument, which can be attached to any future Earth-imaging spacecraft. Goddard Space Flight Center's AETD developed the LAC instrument. AETD will provide open access to U.S. industry regarding the design and performance of LAC, with the explicit purpose of expediting technology transfer to the commercial sector.

EO-1 References

EO-1 Special Issue of *IEEE Trans. Geosci. Remote Sens.*, June 2003.

EO-1 Data Products

Product Name or Grouping	Processing Level	Coverage	Spatial/Temporal Characteristics
ALI/Hyperion/LAC *ALI Data Set Start Date: March 16, 2001; Hyperion Data Set Start Date: May 1, 2001*			
ALI Radiometric	1R	Global	37 km × 42* km/ 16-day repeat
Hyperion Radiometric	1R	Global	7.7 km × 42* km/ 16-day repeat
LAC**	N/A	Global	185 km × 42* km/ 16-day repeat

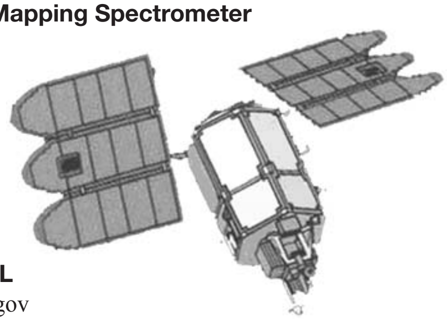
* 42 km is standard length of Data Products, but the length can be adjusted

** LAC data were collected during the original mission but are not being collected or distributed during the extended mission—e.g., since 12/2001

EO-1 Data Products

EP/TOMS

Earth Probe /
Total Ozone Mapping Spectrometer



EP/TOMS URL
toms.gsfc.nasa.gov

Summary

EP/TOMS provides global measurements of total-column ozone and its variation on a daily basis. Together with TOMS aboard Nimbus-7 and Meteor-3, it provides a long-term data set of daily ozone over about two decades. In addition to ozone, TOMS measures sulfur dioxide released in volcanic eruptions, aerosols from desert dust, and smoke from biomass burning and forest fires. The extremely high quality of TOMS ozone data has also helped scientists in detecting a small but steady long-term depletion of the ozone layer over several parts of the globe, including most of the heavily populated areas in the northern mid-latitudes.

Instrument

Total Ozone Mapping Spectrometer (TOMS)

Point of Contact

- *EP/TOMS Principal Investigator:* Richard McPeters, NASA Goddard Space Flight Center

Other Key Personnel

- *EP/TOMS Program Scientist:* Michael Kurylo, NASA Headquarters
- *EP/TOMS Program Executive:* Lou Schuster, NASA Headquarters

Mission Type

Earth Observing System (EOS) Systematic Measurements

Key EP/TOMS Facts

Orbit (after 12/13/97):
- Type: Sun-synchronous
- Altitude: 740 km
- Inclination: 98.385°
- Period: 99.65 minutes
- FOV at Nadir: 39-km latitude × 39-km longitude

Original Orbital Characteristics (before 12/5/97):
- Apogee Altitude: 515.2 km
- Perigee Altitude: 490.5 km
- Orbit Inclination: 97.432°
- Period: 94.6 minutes
- FOV at Nadir: 26-km latitude × 26-km longitude

Design Life: 2 years

Operating Status: Operational

Data Coverage: 7/25/1996–Present (not all dates within this period are available)

Launch

Date and Location: July 2, 1996, from Vandenberg Air Force Base, California

Relevant Science Focus Areas

(see NASA's Earth Science Program section)

- Atmospheric Composition

Related Applications

(see Applied Sciences Program section)

- Air Quality
- Public Health

EP/TOMS Background

Ozone, a molecule made up of three oxygen atoms, shields life on Earth from the harmful effects of the ultraviolet radiation of the Sun. The increased amounts of ultraviolet radiation that reach Earth's surface because of ozone depletion can increase the incidence of skin cancer and cataracts in humans, harm crops, and interfere with marine life.

Researchers face two crucial problems in ozone studies—finding a slow, long-term trend among a variety of short-term trends, and ascertaining how much of the change in global ozone is due to human activities and how much is attributable to natural atmospheric processes. In order to separate these factors, scientists must record data over at least a complete solar cycle, eleven years. TOMS instruments aboard the Nimbus-7 and Meteor-3 satellites have proved invaluable in meeting this requirement.

History

EP/TOMS was launched in July 1996 and continues NASA's long-term daily mapping of the global distribution of Earth's atmospheric ozone. EP/TOMS takes high-resolution measurements of the total-column amount of ozone from space that began with NASA's Nimbus-7 satellite in 1978 and continued with TOMS aboard a Russian Meteor-3 satellite until the instrument stopped working in December 1994. Ozone monitoring in the future will be continued by the Ozone Mapping and Profiler Suite (OMPS), an instrument that will be flown by NOAA under the NPOESS program. The TOMS instrument has mapped in detail the global ozone distribution as well as the Antarctic 'ozone hole,' which forms September through November of each year.

TOMS is a second-generation back-scatter ultraviolet ozone sounder. TOMS can measure 'total-column ozone'—the total amount of ozone in a 'column' of air from Earth's surface to the top of the atmosphere—under all daytime observing and geophysical conditions. TOMS observations cover the near-ultraviolet region of the electromagnetic spectrum, where sunlight is absorbed only partially by ozone.

The extremely high quality of TOMS ozone data has also helped scientists in detecting small but steady long-term damage to the ozone layer over several parts of the globe, including most of the heavily populated areas in the northern mid-latitudes. The discovery of this damage led to the curtailment of the production of ozone-depleting chemicals through an international treaty signed in Montreal in the 1980s.

TOMS

Total Ozone Mapping Spectrometer

TOMS is a NASA-developed instrument that measures total ozone by observing both incoming solar energy and back-scattered ultraviolet (UV) radiation at six wavelengths. 'Back-scattered' radiation is solar radiation that has penetrated into Earth's atmosphere and is then scattered by air molecules and clouds back through the atmosphere to the satellite sensors. Along that path, a fraction of the UV is absorbed by ozone. By comparing the amount of back-scattered radiation to observations of incoming solar energy at identical wavelengths, scientists can calculate Earth's UV albedo, the ratio of light reflected by Earth compared to the amount it receives. Changes in albedo at the selected wavelengths can be used to derive the amount of atmospheric ozone.

TOMS makes 35 measurements every 8 seconds, each covering 50–200 km width on the ground, strung along a line perpendicular to the motion of the satellite. Almost 200,000 daily measurements cover every spot on Earth except polar areas experiencing 24 hours a day of darkness.

Heritage instruments include Nimbus-7/TOMS and Meteor-3/TOMS.

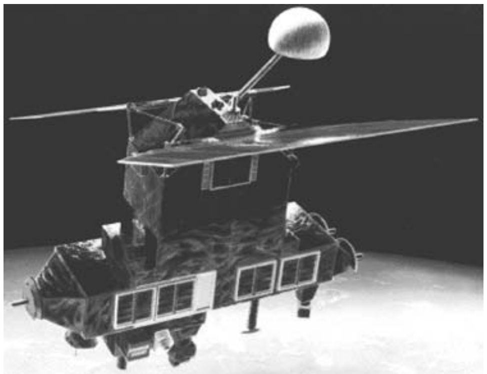
TOMS Data URL

toms.gsfc.nasa.gov/eptoms/ep.html

EP/TOMS Data Set Start Date: July 25, 1996

ERBS

Earth Radiation Budget Satellite



ERBS URLs

asd-www.larc.nasa.gov/erbe/ASDerbe.html
lposun.larc.nasa.gov/erbeweb

Key ERBS Facts

Heritage:

Earth Radiation Budget Experiment (ERBE): Nimbus-7 ERB

Stratospheric Aerosol and Gas Experiment (SAGE II): SAGE I, Stratospheric Aerosol Measurement (SAM II)

Orbit:

Type: Non-sun-synchronous

Inclination: Mid-inclination 57°

Altitude: 585 km

Period: 96.3 minutes

Power: 622 W, quiescent W

Design Life: 1–2 years

Operating Status:

ERBE Scanner operated for 5.5 years

ERBE Non-scanner continues to operate

ERBE Solar Monitor continues to operate

SAGE II continues to operate

Instruments

- Earth Radiation Budget Experiment (ERBE)
- Stratospheric Aerosol and Gas Experiment (SAGE II)

Mission Type

Earth Observing System (EOS) Systematic Measurements

Points of Contact

- *ERBE Mission Scientist:* Robert B. Lee III, NASA Langley Research Center
- *SAGE II Science Mission Manager:* Joseph Zawodny, NASA Langley Research Center

Other Key Personnel

- *ERBS Program Scientist:* Donald Anderson, NASA Headquarters
- *ERBS Program Executive:* Lou Schuster, NASA Headquarters
- *ERBS Mission Director:* Julio Marius, NASA Langley Research Center

Launch

- *Date and Location:* October 5, 1984, from Kennedy Space Center, Florida
- *Vehicle:* Space Shuttle Challenger

Relevant Science Focus Areas

(see NASA's Earth Science Program section)

- Climate Variability and Change
- Atmospheric Composition
- Water and Energy Cycles

Related Applications

(see Applied Sciences Program section)

- Air Quality
- Public Health
- Energy Management

ERBS Mission Background

ERBS was part of NASA's three-satellite Earth Radiation Budget Experiment (ERBE). ERBE was designed to investigate how energy from the Sun is absorbed and re-emitted by Earth. This process of absorption and re-radiation is one of the principal drivers of Earth's climate and weather patterns. Observations from ERBS are also used to determine the effects of human activities (such as burning fossil fuels and the use of chlorofluorocarbons [CFCs]) and natural occurrences (such as volcanic eruptions) on Earth's radiation balance.

As a platform of opportunity, the ERBS mission also carried the Stratospheric Aerosol and Gas Experiment II (SAGE II). The goal of SAGE II was to provide the scientific community with a long-term, global depiction of the distribution of aerosol, ozone, water vapor, and nitrogen dioxide. Thus, SAGE II provides unique and crucial input to the understanding of global, seasonal-to-interannual variability in climate and, in particular, trends in stratospheric ozone. SAGE II recently celebrated its 20th year in orbit.

The Sun's radiant energy is the fuel that drives Earth's climate engine. The Earth-atmosphere system constantly adjusts toward maintaining a balance between the energy that reaches Earth from the Sun and the energy that flows from Earth back out to space. Energy received from the Sun is mostly in the visible (or shortwave) portion of the electromagnetic spectrum. About 30% of the solar energy that comes to Earth is reflected back to space. The ratio of reflected-to-incoming energy is called 'albedo' from the Latin word meaning whiteness. The solar radiation absorbed by Earth causes the planet to heat up until it is radiating (or emitting) as much energy back into space as it absorbs from the Sun. Earth's thermal emitted radiation is mostly in the infrared (or longwave) portion of the spectrum. The incoming and outgoing energy make up Earth's radiation budget.

In the 1970s, recognizing the importance of improving our understanding of the radiation budget and its effects on Earth's climate, NASA established the ERBE mission. The goals of ERBE were to develop and operate a new generation of satellite instrumentation to make accurate regional and global measurements of the components of Earth's radiation budget.

Stratospheric aerosols measured by SAGE II affect the atmospheric energy balance by scattering and absorbing solar and terrestrial radiation. They can also alter stratospheric chemical cycles by catalyzing heterogeneous reactions that markedly perturb nitrogen, chlorine, and ozone levels. In addition, the atmospheric gases measured by SAGE II are significant participants in Earth's atmospheric chemical cycles and in Earth radiation processes.

History

ERBS carried the first ERBE instruments and was launched by the Space Shuttle Challenger in 1984. ERBE instruments were also launched on two National Oceanic and Atmospheric Administration (NOAA) weather monitoring satellites, NOAA 9 and NOAA 10, in 1984 and 1986, respectively.

The ERBS/ERBE scanner instrument was operational for more than five years (October 5, 1984, to February 28, 1990), during which time it provided a substantially improved level of accuracy for multi-year mapping of regional radiation budgets over the globe. The ERBS/ERBE non-scanner continues to operate. The multi-year history of ERBS non-scanner measurements is providing the long-term trends of Earth's emitted and reflected radiant energy at large (global and zonal) spatial scales. Also, ERBS solar monitor measurements are continuing to show the trends in the solar constant. The long-term record of Earth radiation established by ERBE is being continued and improved by its successor, the Clouds and the Earth's Radiant Energy System (CERES).

SAGE II data, in conjunction with data from sister instruments SAM II and SAGE I, have been used to estimate long-term constituent trends and identify responses to episodic events such as volcanic eruptions. Major results of these programs include illustration of the stratospheric impact of the 1991 Mount Pinatubo eruption, identification of a negative global trend in lower stratospheric ozone during the 1980s, and quantitative verification of the positive water-vapor feedback in current climate models. The constituent record provided by SAGE II is being continued and improved by its successor SAGE III.

ERBE

Earth Radiation Budget Experiment

Two types of instruments were developed:

- *Scanner*–Three co-planar detectors (Earth longwave, shortwave, and total)
- *Non-scanner*–Five detectors (One solar total, two Earth shortwave, two Earth longwave)

The ERBE scanner instrument normally operated in a cross-track mode, scanning from above the horizon, down across the Earth disk, through nadir, continuing across the other Earth limb up through space to the internal blackbody. In-flight, the instrument was normally calibrated (internally) at 2-week intervals. The scanning detectors used are as follows:

1) One total-wavelength thermistor bolometer
2) One long-wavelength thermistor bolometer
3) One short-wavelength thermistor bolometer

The total detector measures radiation in the 0.2–50.0 μm wavelength band; the longwave detector measures radiation in the 0.5–50.0 μm wavelength band; and the shortwave detector measures radiation in the 0.2–5.0 μm band.

The ERBE non-scanner instrument included four detectors for Earth viewing and operated in a nadir, Earth-staring mode. The fifth detector (the solar monitor) was used only for solar calibration measurements. In-flight, the instrument was normally calibrated internally at 2-week intervals. The five detectors were as follows:

Wide Field-Of-View (WFOV) Earth-viewing Detectors:
1) One total-wavelength active-cavity radiometer (ACR)
2) One short-wavelength ACR

Medium Field-Of-View (MFOV) Earth-viewing Detectors:
3) One total-wavelength ACR
4) One short-wavelength ACR

Solar Monitor Detector:
5) One solar active-cavity pyrheliometer

The total detectors measure radiation in the 0.2–50.0 µm wavelength band, and the shortwave detectors measure radiation in the 0.2–5.0 µm band. The solar monitor is sensitive to all incident irradiance.

Over its operational life, ERBS/ERBE data products were validated and produced for use by the science community. These products range from instantaneous time-sequenced instrument measurements to monthly-averaged regional, zonal, and global estimates of radiation budget parameters including:

- Solar Incidence (Product name S-2)
- Regional, Zonal, and Global Averages (S-4)
- Regional, Zonal, and Global Gridded Averages (S-4G)
- Medium-Wide Field of View Non-scanner Data (S-7)
- Instantaneous Scanner and Non-scanner Data (S-8)
- Scanner Earth Radiant Flux and Albedo (S-9)
- Non-scanner Earth Radiant Flux and Albedo (S-10)

These data products are available from the NASA Langley Research Center (LaRC) Distributed Active Archive Center (DAAC). Data, programs for reading the data, and user's guides can be obtained through the on-line system.

ERBE URLs

Instrument: asd-www.larc.nasa.gov/erbe/ASDerbe.html.

Data: eosweb.larc.nasa.gov/PRODOCS/erbe/table_erbe.html.

ERBE Non-scanner Data Set Start Date: October 14, 1984

ERBE Non-scanner Data Set End Date: August 31, 2005

ERBE Scanner Data Set Start Date: November 5, 1984

ERBE Scanner Data Set End Date: February 28, 1990

SAGE II

Stratospheric Aerosol and Gas Experiment II

During each sunrise and sunset encountered by the orbiting spacecraft, the SAGE II instrument uses the solar-occultation technique to measure attenuated solar radiation through Earth's limb in seven channels centered at wavelengths ranging from 0.385 µm to 1.02 µm. The exo-atmospheric solar irradiance is also measured in each channel during each event for use as a reference in determining limb transmittances.

The SAGE II instrument is a seven-channel Sun photometer using a Cassegrainian-configured telescope, holographic grating, and seven silicon photodiodes, some with interference filters, to define the seven spectral channel band passes. Solar radiation is reflected off a pitch mirror into the telescope with an image of the Sun formed at the focal plane. The instrument's instantaneous field-of-view, defined by an aperture in the focal plane, is a 0.5 × 2.5 arc-minute slit that produces a vertical resolution at the tangent point on Earth's horizon of about 0.5 km. Radiation passing through the aperture is transferred to the spectrometer section of the instrument containing the holographic grating and seven separate detector systems. The holographic grating disperses the incoming radiation into the various spectral regions centered at the 385, 448, 453, 525, 600, 940, and 1020 nm wavelengths. Slits on the Rowland circle of the grating define the spectral band pass of the seven spectral channels. The spectrometer system is inside the azimuth gimbal to allow the instrument to be pointed at the Sun without image rotation. The azimuth gimbal can be rotated over 370° so that measurements can be made at any azimuth angle.

The operation of the instrument during each sunrise and sunset measurement is totally automatic. Prior to each sunrise or sunset encounter, the instrument is rotated in azimuth to its predicted solar-acquisition position. When the Sun's intensity reaches a level of one percent of maximum in the Sun sensor, the instrument adjusts its azimuth position to lock onto the radiometric center of the Sun to within ±45 arc-seconds and then begins acquisition of the Sun by rotating its pitch mirror in a predetermined direction, depending on whether it is a sunrise or a sunset. When the Sun is acquired, the pitch mirror rotates back and forth across the Sun at a rate of about 15 arc-minutes per second. The radiometric channel data are sampled at a rate of 64 samples per second per channel, digitized to 12-bit resolution, and recorded for later transmission back to Earth.

SAGE II URLs

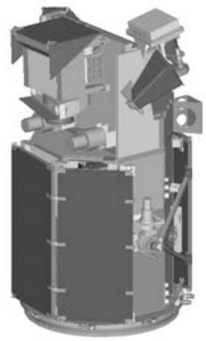
Instrument: www-sage2.larc.nasa.gov/.

Data: eosweb.larc.nasa.gov/PRODOCS/sage2/table_sage2.html.

SAGE II Data Set Start Date: October 24, 1984

SAGE II Data Set End Date: August 22, 2005

Glory



Glory URL
glory.gsfc.nasa.gov/

Summary

The Glory satellite consists of a spacecraft bus and three instruments and will be launched from the Vandenberg Air Force Base aboard a Taurus 2110 launch vehicle. Glory's remote sensing mission is designed to: 1) collect data on the optical, microphysical, and chemical properties, and spatial and temporal distributions of aerosols and clouds; and 2) continue the long-term total solar irradiance climate record.

Instruments

- Aerosol Polarimetry Sensor (APS)
- Cloud Camera (CC)
- Total Irradiance Monitor (TIM)

Points of Contact

- *Glory Project Scientist:* Michael Mishchenko, NASA Goddard Institute for Space Studies
- *APS Instrument Scientist:* Brian Cairns, NASA Goddard Institute for Space Studies
- *TIM Instrument Scientist:* Greg Kopp, Laboratory for Atmospheric and Space Physics/University of Colorado (Boulder)

Other Key Personnel

- *Glory Program Scientist:* Hal Maring, NASA Headquarters
- *Glory Program Executive:* Ronald Hooker, NASA Headquarters
- *Glory Project Manager:* Bryan Fafaul, NASA Goddard Space Flight Center

Mission Type

Earth Observing System (EOS) Systematic Measurements

Key Glory Facts

Orbit:
Type: Sun-synchronous
Equatorial Crossing: 1:35 p.m.
Altitude: 705 km ± 30 km
Inclination: 98.2° ± 0.15°
Period: 99 minutes
Repeat Cycle: 16 days

Dimensions: 1.9 m × 1.4 m × 1.4 m

Mass: 482 kg at launch

Power: 320 W

Downlink: X-Band/S-Band

Design Life: 3 years with a 5-year goal

Glory Partners

Space Network: The Tracking Data and Relay Satellite System operated by NASA's Space Network

Mission Operations Center (MOC): Based at the mission operations support contractor facility; the sole facility for the operation of the spacecraft and the generation of the command uplink

Ground Station: Commercial ground stations for the space-to-ground RF communications with the satellite; primary ground station in Alaska, backup in Norway

APS Science Operations Center (SOC): NASA GISS

TIM SOC: Colorado University-Boulder's Laboratory for Atmospheric and Space Physics

Data Archive and Distribution: NASA Goddard Earth Sciences Distributed Active Archive Center (GES DAAC)

Ground Segment: Combination of the commercial ground stations, MOC, APS SOC, TIM SOC, GES DAAC, and networks that connect them

Launch

- *Date and Location:* No earlier than 2008, from Vandenberg Air Force Base, California
- *Vehicle:* Taurus 2110

Relevant Science Focus Areas
(see NASA's Earth Science Program section)

- Atmospheric Composition
- Carbon Cycle, Ecosystems, and Biogeochemistry
- Climate Variability and Change
- Water and Energy Cycles

Related Applications
(see Applied Sciences Program section)

- Air Quality
- Carbon Management
- Ecological Forecasting
- Invasive Species
- Public Health

Glory Science Goals

- Analyze aerosols and aerosol-cloud interactions with data collected on the optical, microphysical, and chemical properties of aerosols and clouds.
- Measure total solar irradiance for long-term climate studies.

Glory Mission Overview

Glory is a remote sensing spaceflight mission designed to 1) collect data on the optical, microphysical, and chemical properties and spatial and temporal distributions of aerosols and clouds; and 2) continue collection of total solar irradiance data for the long-term climate record. The mission will accomplish these objectives by deploying two separate science instruments aboard a Low Earth Orbit (LEO) satellite: the Aerosol Polarimetry Sensor (APS) and the Total Irradiance Monitor (TIM).

APS will collect global aerosol and cloud data based on multi-angle, along-track polarimetric and radiometric measurements taken within the solar reflective spectral region (0.4–2.4 µm). Measurements of spectral polarization and radiance are restricted to the sunlit portion of the orbit; and, since clouds can have a significant impact on the quality of polarimetric retrievals, an onboard cloud camera is used to distinguish between clear and cloud-affected scenes. A three-year mission life (five-year goal) provides the minimum duration to observe seasonal and regional trends and characterize the evolution of aerosols during transient climate events (El Niño, volcanic eruptions, etc.).

TIM will collect high accuracy, high precision measurements of total solar irradiance (TSI) using an active cavity radiometer that monitors changes in incident sunlight to Earth's atmosphere. Because TIM is designed to operate nominally in a solar-viewing orientation, it is mounted on a gimbaled platform that accommodates targeting independent of the spacecraft's nadir viewing attitude. TIM is a heritage-design instrument that was originally flown on the SORCE satellite launched in January 2003.

The Glory satellite will be flown in a nominal 705 km, sun-synchronous orbit with a nominal ascending node (south to north

Glory Instruments

APS
Aerosol Polarimetry Sensor

APS is a multi-spectral polarimetric sensor that has the capability to collect visible, near-infrared, and short-wave infrared polarized radiometric data scattered from aerosols and clouds. APS is a continuous scanning sensor designed to make along-track, multi-angle observations of Earth and atmospheric scene spectral polarization and radiance.

Cloud Camera

The cloud camera is a dual-band, visible imager utilizing a non-scanning staring detector array that is analogous to a star tracker, but Earth-viewing. It consists of an optical imaging system that provides continuous cross-track coverage over a narrow swath centered on the APS along-track footprint.

TIM
Total Irradiance Monitor

TIM is an active cavity radiometer that records total solar irradiance. It has four identical radiometers to provide redundancy and to help detect changes in the instrument response caused by exposure to solar radiation. Each radiometer consists of a 0.5-cm^2 precision aperture followed by an absorptive cavity. TIM is mounted on a two-axis, gimbaled platform that allows it to point the instrument independent of the spacecraft bus attitude.

equatorial crossing) at 1:35 p.m. mean local time. This orbit was selected to coordinate observations made by the MODIS instrument on NASA's Aqua satellite with APS. From this altitude, the APS scanning sensor generates along-track, multi-angle photopolarimetric measurements with a ~5.6 km circular geometric instantaneous field of view. The sensor scans Earth over a nominal field of view of ±50° about nadir collecting a minimum of 240 angular samples per revolution with overlap of the individual swaths.

The Glory satellite will consist of a spacecraft bus and three instruments (APS, TIM, and cloud camera). It will be launched from the Western Test Range at Vandenberg Air Force Base (VAFB) aboard a Taurus 2110 launch vehicle. After the satellite has been placed into orbit, a 30-day in-orbit checkout begins. Verification of initial insertion parameters and early orbit ephemeredes will be made using the NASA Flight Dynamics Facility. Normal science operations immediately follow successful checkout. During that period, science data collection takes place on a near-continuous basis, interrupted only by special operations and anomalies. Mission operations and control are performed through the Mission Operations Center (MOC) located at the mission operations support contractor facility.

Ground station contacts are nominally required once per day permitting single-shift support and minimizing overall spacecraft operations. Mission planning, routine state of health monitoring, and spacecraft commanding are accomplished by the spacecraft contractor with instrument command files provided electronically by APS and TIM science operations centers (SOCs). The spacecraft is designed for automatic safing in the event of anomalies or critical failures.

A commercial ground station network will be used for the Glory mission with the primary terminal located in Fairbanks, Alaska and the backup terminal located in northern Norway. The ground station supports both low-rate S-Band command and telemetry link and high-rate X-Band return-only science downlink of 28 Mbps. A high-rate (2 Mbps) S-Band science data backup downlink is also supported. The primary ground station provides sufficient coverage for all nominal mission operations and science downlinks plus additional passes for on-orbit activation and checkout, anomaly resolution, or additional science downlink, as required. The Space Network's geosynchronous Tracking and Data Relay Satellite System (TDRSS) provides communications support to the Glory mission during early on-orbit operations and in contingency situations.

Science data are recorded at the ground system and routed to SOCs. Once received at SOCs, calibration of the science data is performed and science data processing algorithms are applied. Retrieval of MODIS and OMI data from the NASA GSFC Earth Sciences Distributed Active Archive Center (GES DAAC) and science data from other sources is performed by SOCs, as required, to generate the necessary data products. After resulting data products are validated and assessed for accuracy by the science teams, final data products are archived and distributed to the user community by the GES DAAC. The TIM data products are independent of any other instrument and are expected to be released within a week of data acquisition.

Key APS Facts

Heritage: Pioneer–Venus OCPP, Research Scanning Polarimeter (RSP; airborne version of APS)

Instrument Type: Spectrophotopolarimeter

Scan Type: Along track

Incidence Viewing: + 60°/- 80° view zenith range at Earth's surface. (Operationally use ± 60° because that maintains pixel size at less than 20 km; pixel size at 80° is 90 km.)

Calibration: Onboard polarimetric calibration and radiometric stability tracking

Field of Regard: + 50°/- 62° from nadir at satellite

Instrument IFOV: 8 mrad

Transmission Rate: N/A

Swath: 5.6 km cross track, 2800 km along track (1850 km operational range)

Spatial Resolution: 5.6 km at nadir

Spectral Range: 0.4–2.2 μm

Measurement Type: Stokes parameters I, Q and U simultaneously in all spectral bands

Dimensions: 51.7 cm × 58.6 cm × 48.2 cm

Mass: 58 kg

Power: 45 W

Duty Cycle: 55%

Data Rate: <160 kbps average

Direct Broadcast: No

APS

Aerosol Polarimetry Sensor

Aerosol Research

Aerosols play a crucial role in climate forcing and can contribute to both warming and cooling of Earth's atmosphere. Black carbon aerosols can contribute to global warming by absorbing the Sun's radiation and re-radiating the Sun's energy as infrared radiation that is trapped by Earth's atmosphere in much the same way that the windshield of an automobile contributes to a parked automobile heating up under the summer's Sun. Sulfate aerosols, produced from the sulfur dioxide gas that spews out of a volcano or from the burning of sulfur-bearing fossil fuels, reflect the Sun's radiation out into space and typically cause cooling. Aerosols, unlike greenhouse gases, have a short lifetime in the atmosphere. After they are produced they may interact with other atmospheric constituents including gases, particularly water vapor, other aerosols, and cloud particles, and are transported by the winds before being removed from the atmosphere by sedimentation or rainout over periods on the order of a week. Because of both natural and anthropogenic events, aerosols are constantly being replenished and the anthropogenic aerosols, since the beginning of the industrial age, have been increasing. Aerosols can also play a critical role in precipitation, but, similar to the effect on temperature, some species of aerosols may increase precipitation, while others may inhibit precipitation. While it is recognized that aerosols play a key role, because of the uncertainty of the composition of the aerosols in the atmosphere there remains great uncertainty regarding the net effect that atmospheric aerosols have on climate—hotter or cooler, more rain or less.

In the framework of the Climate Change Research Initiative (CCRI), initiated in June 2001 to study areas of uncertainty about global climate change, research on atmospheric concentrations and effects of aerosols is specifically identified as a top priority. One of the activities CCRI identifies to support this research is improving observations for model development and applications from observing systems. To that end, the Glory mission will deploy an instrument that will collect data to help understand the climate-relevant chemical, microphysical, and optical properties, and spatial and temporal distributions of human-caused and naturally occurring aerosols. Specifically, Glory will be used to determine:

1) The global distribution of natural and anthropogenic aerosols (black carbons, sulfates, etc.) with accuracy and coverage sufficient for reliable quantification of:
   - the aerosol effect on climate
   - the anthropogenic component of the aerosol effect
   - the potential secular trends in the aerosol effect caused by natural and anthropogenic factors

2) The direct impact of aerosols on the radiation budget and its natural and anthropogenic components

3) The effect of aerosols on clouds (lifetime, microphysics, and precipitation) and its natural and anthropogenic components

Key Cloud Camera Facts

Heritage: Calipso Cloud Camera, Star tracker cameras.

Instrument Type: Spectroradiometer

Scan Type: Earth imaging

Incidence Viewing: Push broom imager

Calibration: Lunar views

Field of View (FOV): ± 9° cross track

Instrument IFOV: > 0.6 mrad

Transmission Rate: N/A

Swath: ±125 km cross track

Spatial Resolution: 500 m

Spectral Range: 443 and 865 nm bands

Dimensions: TBD

Mass: 3 kg

Power: < 10 W

Duty Cycle: 50%

Data Rate: < 216 kbps maximum

Direct Broadcast: No

4) The feasibility of improved techniques for the measurement of black carbon and dust absorption, to provide more accurate estimates of their contribution to the climate forcing function

In addition to the aerosol science objectives, Glory will be used to provide proof of concept and risk reduction for the NPOESS APS.

APS Data

The APS data products, or Environmental Data Records (EDRs), are:

For threshold science requirements—

1) Aerosol optical thickness
2) Aerosol particle size
3) Aerosol refractive index, single-scattering albedo, and shape
4) Cloud optical thickness
5) Cloud particle size distribution

For science goals—

1) Single scattering albedo derived from ocean glint
2) Single-scattering albedo derived from the 412/443 nm aerosol differential absorption technique
3) Aerosol optical thickness derived from APS-MODIS combined inversion
4) Fraction of fine mode aerosol derived from APS-MODIS combined inversion

Aerosols are defined as suspensions of liquid droplets or solid particles in the atmosphere. Aerosols include, but are not limited to, smoke, dust, sand, volcanic ash, sea spray, polar stratospheric clouds, and smog. Although cloud particles can be considered as a particular type of aerosol, it is conventional to put them in a separate category. Specifically, liquid water clouds are defined as distinct optically thick particulate features composed of droplets with radii on the order of 10 µm in size. Cirrus clouds are defined as visible or sub-visible particulate layers (either natural or man-made, such as contrails), which reside in the upper troposphere/lower stratosphere and are composed of water ice crystals with sizes ranging from several µm to 1 mm.

Key TIM Facts

Heritage: SORCE

Instrument Type: Electrical substitution radiometer

Scan Type: Pointing

Incidence Viewing: Sun-viewing

Calibration: Deep space view

FOV: 3.6° working cone

Instrument IFOV: N/A

Transmission Rate: N/A

Swath: N/A

Spatial Resolution: N/A

Spectral Range: Total (1 nm–1000 µm)

Dimensions: 17.7 cm × 27.9 cm × 27.2 cm

Mass: 64 kg

Power: 75 W (average)

Duty Cycle: 100%

Data Rate: 539 bps

Direct Broadcast: No

Cloud Camera

Cloud Camera Research

The cloud camera is a high-spatial-resolution two-band radiometer intended to facilitate the identification of cloud-contaminated APS pixels and to determine the fraction of the pixel area occupied by clouds. Over ocean, the cloud camera will be used to determine aerosol load and fine mode fraction based on the aerosol microphysical model determined from APS measurements.

Cloud Camera Data

The analysis of cloud camera data to provide cross track coverage over a finite swath of aerosol load and fine mode fraction over the open ocean provides a back up to what is planned with APS and MODIS in the event that MODIS data are not available.

TIM

Total Irradiance Monitor

TIM Research

TSI, together with the absorption and reflection of this radiation by Earth's atmosphere, determines the global average temperature of Earth. The climate of Earth is directly affected by the balance between the intensity of the Sun and the response of the atmosphere. Changes in either the solar irradiance or the composition of the atmosphere can cause global climate change. Solar irradiance is purely a natural phenomenon, while the composition of the atmosphere is strongly influenced by the byproducts of modern industrial societies. Over the past century, the average surface temperature of Earth has increased by about 0.5° C. Understanding the portion of the increase in temperature and the concomitant climate change due to natural causes is of primary importance to the establishment of scientifically and economically effective policy.

The continued measurement of TSI to determine the Sun's direct and indirect effects on Earth's climate, at current state-of-the-art accuracy and without temporal gaps in the dataset, constitutes the solar irradiance requirement for the Glory mission. It is essential that there be no temporal gaps in the data, as any measured changes in the atmospheric temperature must be appropriately interpreted in the context of any changes in the solar irradiance.

TIM Requirements

The fundamental requirement for TIM is to make precise and accurate daily measurements of TSI and connect them to previous TSI measurements to form the long-term climate record. TSI measurement requirements are based on the requirement that the Glory TIM serve as continuity between the five-year SORCE TIM, in orbit since 2003, and the NPOESS TIM, scheduled to begin operations in 2013. Technically, this mandates that the absolute accuracy (±100 ppm) and the relative accuracy (10 ppm) be maintained and that the Glory TIM provide calibrated overlap by more than six months with the heritage mission and the future mission.

Glory References

Chowdhary, J., B. Cairns, M. Mishchenko, and L. D. Travis, 2001: Retrieval of aerosol properties over the ocean using multispectral and multiangle photopolarimetric measurements from the Research Scanning Polarimeter. *Geophys. Res. Lett.*, **28**, 243–246.

Chowdhary, J., B. Cairns, and L. D. Travis, 2002: Case studies of aerosol retrievals over the ocean from multiangle, multispectral photopolarimetric remote sensing data. *J. Atmos. Sci.*, **59**, 383–397.

Kaufman, Y. J., J. V. Martins, L. A. Remer, M. R. Schoeberl, and M. A. Yamasoe, 2002: Satellite retrievals of aerosol absorption over the oceans using sunglint. *Geophys. Res. Lett.*, **29**, 1928.

Kopp, G., and G. Lawrence, 2005: The Total Irradiance Monitor (TIM): instrument design. *Solar Phys.*, **230**, 91–109.

Kopp, G., G. Lawrence, and G. Rottman, 2005: The Total Irradiance Monitor (TIM): science results. *Solar Phys.*, **230**, 129–140.

Mishchenko, M. I., and L. D. Travis, 1997: Satellite retrieval of aerosol properties over the ocean using polarization as well as intensity of reflected sunlight. *J. Geophys. Res.*, **102**, 16,989–17,013.

Mishchenko, M. I., B. Cairns, J. E. Hansen, L. D. Travis, R. Burg, Y. J. Kaufman, J. V. Martins, and E. P. Shettle, 2004: Monitoring of aerosol forcing of climate from space: analysis of measurement requirements. *J. Quant. Spectrosc. Radiat. Transfer*, **88**, 149–161.

Glory Data Products

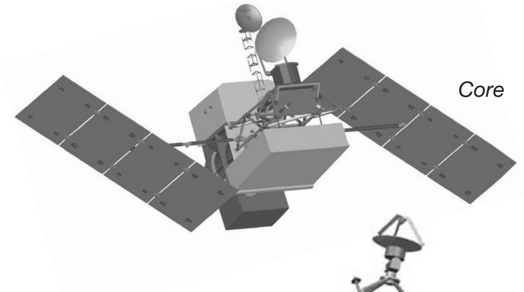
Product Name or Grouping	Processing Level	Coverage	Spatial/Temporal Characteristics
APS			
Aerosol optical thickness at wavelengths in the 0.4–2.2 μm range	2	Restricted to 5.6-km swath along satellite ground track	5.6 km IFOV at nadir viewed from multiple angles
Aerosol particle size distribution	2	Restricted to 5.6-km swath along satellite ground track	5.6 km IFOV at nadir viewed from multiple angles
Aerosol particle refractive index, single-scattering albedo, and shape	2	Restricted to 5.6-km swath along satellite ground track	5.6 km IFOV at nadir viewed from multiple angles
Liquid cloud optical thickness	2	Restricted to 5.6-km swath along satellite ground track	5.6 km IFOV at nadir viewed from multiple angles
Liquid cloud particle size distribution	2	Restricted to 5.6-km swath along satellite ground track	5.6 km IFOV at nadir viewed from multiple angles
Single-scattering albedo derived from the ocean glint observations	2	As appropriate, dictated by observing opportunities	As appropriate, dictated by observing opportunities
Single-scattering albedo derived from the spectral contrast technique	2	Restricted to 5.6-km swath along satellite ground track	5.6 km IFOV at nadir viewed from multiple angles
Aerosol optical thickness derived from APS-VIIRS combined inversion *(see note below)*	2	Restricted to ±100-km swath along satellite ground track	5.6 km IFOV at nadir viewed by APS from multiple angles; cross-track radiance-only measurements by VIIRS
Fraction of fine mode aerosol derived from APS-VIIRS combined inversion *(see note below)*	2	Restricted to ±100-km swath along satellite ground track	5.6 km IFOV at nadir viewed by APS from multiple angles; cross-track radiance-only measurements by VIIRS
APS and Cloud Camera			
Aerosol optical thickness derived from APS-VIIRS combined inversion	2	Restricted to ±100-km swath along satellite ground track	5.6 km IFOV at nadir viewed by APS from multiple angles; cross-track radiance-only measurements by the Cloud Camera
Fraction of fine mode aerosol derived from APS-VIIRS combined inversion	2	Restricted to ±100-km swath along satellite ground track	5.6 km IFOV at nadir viewed by APS from multiple angles; cross-track radiance-only measurements by the Cloud Camera
TIM			
Precise and accurate measurements of TSI	2, 3	N/A	Four measurements daily

Note: The Glory satellite will be flown in a nominal 705 km, sun-synchronous orbit with a nominal ascending node (south to north equatorial crossing) at 1:35 p.m. mean local time. This orbit was selected to coordinate observations made by the MODIS instrument on the NASA Aqua satellite with APS.

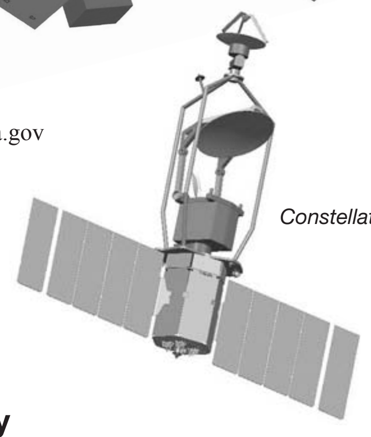
Glory Data Products

GPM

Global Precipitation Measurement Mission



GPM URL
gpm.gsfc.nasa.gov



Summary

GPM builds on the success of the Tropical Rainfall Measuring Mission (TRMM) and will provide more accurate, frequent (3-hourly), global, high spatial resolution, and microphysically detailed measurements of precipitation. An advanced core satellite with a first-of-its-kind dual frequency radar and passive microwave radiometer will provide key measurements of precipitation physics and serve as a calibrator for a set of constellation satellites. Each member of the constellation will carry some type of passive microwave radiometer and will provide global and temporal sampling and also reduce error uncertainty in precipitation measurements. GPM is also composed of a comprehensive precipitation processing system and an international ground validation effort. Scientifically, GPM will provide accurate assessment of the water cycle and improved prediction of weather, climate, and hydrometeorological processes.

Instruments

Core:
- Dual-frequency Precipitation Radar (DPR), JAXA
- GPM Microwave Imager (GMI), NASA

Constellation:
- GPM Microwave Imager (GMI), NASA

Note: In this context, Core and Constellation refer to *two specific spacecraft missions* that represent NASA's contribution to GPM. (See Mission Background section for further clarification.)

Key GPM Core Facts

Heritage: Tropical Rainfall Measuring Mission (TRMM)

Orbit:
- Type: Circular orbit
- Equatorial Crossing: Non-specified
- Altitude: 400 km
- Inclination: 65°
- Period: 92.56 min (nominal 400 km orbit)
- Repeat Cycle: Changes 24 hours of local time in 46-day precession cycle

Dimensions: TBD when spacecraft provider is selected (preliminary designs shown)

Mass: 3200 kg

Power: 1450 W

Design Life: 3 years required; 5-year goal

Average Data Rate: ~300 kbps

Data Storage: 12 hours of science and housekeeping data without loss

Data Relay Methods: Data are returned essentially continuously over a low-rate Tracking and Data Relay Satellite System (TDRSS)-Multi-access (MA) link enabling 'virtual broadcast' of data over the Internet as well as once per orbit via the single-access (SA) service of TDRSS.

Key GPM Constellation Facts

Orbit:
- Type: Circular orbit
- Equatorial Crossing: TBD
- Altitude: ~635 km
- Inclination: Sun-synchronous (TBD)
- Period: 97.42 min
- Repeat Cycle: TBD

Dimensions: TBD when spacecraft provider is selected (preliminary design shown)

Mass: ~500 kg

Power: ~400 W

Design Life: 3 years required; 5-year goal

Average Data Rate: ~50 kbps

Data Storage: 12 hours of science and housekeeping data without loss

Data Relay Methods: Data are returned essentially continuously over a low-rate Tracking and Data Relay Satellite System (TDRSS) Multi-access (MA) link enabling 'virtual broadcast' of data over the Internet.

Points of Contact

- *GPM Project Scientist:* Arthur Hou, NASA Goddard Space Flight Center
- *GPM Deputy Project Scientist:* Marshall Shepherd, NASA Goddard Space Flight Center
- *GPM Deputy Project Scientist for Data Systems:* Erich Stocker, NASA Goddard Space Flight Center

Other Key Personnel

- *GPM Program Scientist:* Ramesh Kakar, NASA Headquarters
- *GPM Program Executive:* Steven Neeck, NASA Headquarters
- *GPM Formulation Manager:* John Durning, NASA Goddard Space Flight Center

Mission Type

Next-generation Systematic Measurement

Launch

- *Date and Location:*

  Core: Date TBD from Tanegashima Space Complex in Tanegashima, Japan

  Constellation: Date TBD, from Vandenberg Air Force Base, California

- *Vehicle:*

  Core: JAXA H-II A launch vehicle

  Constellation: Taurus Class launch vehicle

Relevant Science Focus Areas

(see NASA's Earth Science Program section)

- Climate Variability and Change
- Water and Energy Cycles
- Weather

Related Applications

(see Applied Sciences Program section)

- Agricultural Efficiency
- Aviation
- Disaster Management
- Energy Management
- Public Health
- Water Management

GPM Instruments

GMI

GPM Microwave Imager

A conical-scan, passive microwave radiometer that will be used for rainfall measurements; two identical GMI instruments will be produced, one for Core and one for Constellation.

DPR

Dual-frequency Precipitation Radar

Consists of two essentially independent Precipitation Radars each operating at a different microwave frequency, enabling more detailed measurements of cloud structure and precipitation characteristics than with previous precipitation radar systems.

GPM Science Goals

- *Climate Prediction*—Improve climate prediction through progress in quantifying space-time variability of precipitation along with improvements in achieving water budget closure, plus focused research on relationships between precipitation and climate variations.
- *Weather Prediction*—Improve the accuracy of global and regional numerical weather prediction models through accurate and precise measurements of instantaneous rain rates, made frequently and with global distribution, plus focused research on more advanced techniques in satellite rainfall data assimilation.
- *Flood/Fresh Water Resource Prediction*—Improve flood and fresh water resource prediction through frequent sampling and complete Earth coverage of high-resolution precipitation measurements, plus focused research on more innovative designs in hydro-meteorological modeling.

GPM Mission Background

Water cycling and the future availability of fresh water resources are immense societal concerns that impact every nation on Earth. Furthermore, precipitation is a fundamental component in virtually every environmental issue. Comprehensive information on precipitation is valuable for a wide range of research areas and related applications with practical benefits for society. Unfortunately, precipitation is a difficult meteorological field to measure because precipitation systems tend to exhibit a somewhat random nature and also evolve and dissipate very rapidly. It is not at all uncommon to see a wide range of rain amounts over a very small area; and in any given area, the amount of rain can vary quite a bit over a very short amount of time. These factors make quality precipitation measurements difficult or even impossible to obtain. It's also difficult to obtain reliable ground-based precipitation measurements over regional and global scales because most of the world is covered by water and many countries are not equipped with precision rain measuring sensors (i.e., rain gauges and/or radars). It might be possible to study precipitation over a small area using ground-based data, but rarely beyond that. The only practical way to obtain useful regional and global scale precipitation measurements is from the vantage point of a space-based remote sensing instrument.

Participants from a large number of nations have initiated an effort to develop a next generation, space-based measuring system that can fulfill the requirements for frequent, global, and accurate precipitation measurements that are continuously acquired. The effort, known as the Global Precipitation Measurement (GPM) Mission, involves various space agencies, weather and hydro-meteorological forecast services, research institutions, and individual scientists from around the world. They are working together to develop a flagship satellite mission for a variety of water-research and applications programs. These include support of international research programs involved with the global water and energy cycle, such as the World Climate Research Program (WCRP) Global Energy and Water Cycle Experiment (GEWEX), and Global Earth Observation System of Systems (GEOSS), as well as support of basic research, applications-oriented research, and operational environmental forecasting throughout individual nations and consortia of nations.

GPM Space Hardware

The GPM Mission will have the capability to provide physically based retrievals on a global basis, with ~3-hour sampling assured at any given Earth coordinate ~90% of the time. Such frequent diurnal sampling is made possible by a mixed non-sun-synchronous/sun-synchronous satellite orbit architecture.

The design and development of GPM is an outgrowth of valuable knowledge that has been obtained by TRMM, and published by various U.S., Japanese, and European Union (EU) research teams, and by individual scientists. TRMM was a single satellite, which is less than ideal for making a global measurement of a highly variable meteorological parameter like precipitation. GPM will instead consist of a constellation of satellites, some dedicated solely to GPM and others conveniently available through other experimental and operational missions supported by various space agencies around the world.

GPM Core Satellite—NASA and the Japan Aerospace Exploration Agency (JAXA) are working together to build and launch the GPM Core Satellite (referred to as 'Core' in this section). As was the case with TRMM, the plan is that JAXA will provide the radar and the launch while NASA will provide the radiometer, the satellite bus, and the ground segment. Core is the central rain-measuring observatory of GPM and will fly both a Dual-frequency Precipitation Radar (DPR) and a high-resolution, multi-channel passive microwave (PMW) rain radiometer known as the GPM Microwave Imager (GMI). Core will also serve as the calibration reference system and the fundamental microphysics probe to enable an integrated measuring system with the constellation-support satellites.

Dedicated NASA GPM Constellation Satellite—In addition to Core, NASA will also provide a dedicated member of the constellation (referred to as 'Constellation' in this section.) This is conceived as a relatively small spacecraft that will carry a single radiometer on board. The radiometer will be identical to the GMI on Core.

Other GPM Constellation Members—Besides Constellation, up to seven other missions may be part of the GPM constellation. Other missions are classified as 'satellites of opportunity'. One specific example of a potential satellite of opportunity is the proposed French/Indian mission known as Megha-Tropiques. Each satellite of opportunity has its own unique scientific mission and could also contribute rainfall measurements for GPM. Each satellite in the constellation will carry one or more precipitation sensing instruments. At a minimum, to be a support satellite for the GPM constellation, a mission has to carry some type of passive microwave radiometer measuring several rain frequencies. Estimates are that by the time GPM is fully operational, ten agencies from seven countries and the EU could be participating in the constellation, representing an unprecedented level of international cooperation on a satellite mission.

Proposed ESA EGPM Satellite—The European Space Agency (ESA) and a consortium of European and Canadian scientists have proposed to contribute a European GPM (EGPM) satellite that would add measurement capabilities that complement Core. This observatory would be fitted with an advanced rain radiometer using a mix of window and molecular O_2 sounding frequencies, and an additional high-sensitivity radar. The instruments on EGPM would measure light and warm rainfall, moderate to heavy drizzle, and light to moderate snowfall. All of these types of precipitation make important contributions to Earth's water cycle at mid- to high-latitudes but will be largely undetectable by Core. As of this writing, ESA has not formally selected this mission as part of its program.

GPM Data Processing System

The data information system for GPM is called the GPM Precipitation Processing System (PPS). It builds on the existing mission-specific TRMM Science Data and Information System (TSDIS), but is now a generic framework that can easily be adapted for use on any precipitation mission by adding, deleting, and/or modifying processing threads and equipment suitable to individual mission requirements.

The main responsibilities of the PPS are: 1) to acquire Level 0 and 1 sensor data; 2) to produce and maintain consistent Level 1 calibrated/Earth located radiometer brightness temperatures and radar reflectivities; 3) to process Level 1 data into consistent Level 2 and 3 standard precipitation products; 4) to disseminate precipitation products through both 'push' and 'pull' data transfer mechanisms; and 5) to assure archival of all data products acquired or produced by the PPS—either within the PPS or through suitable arrangements with other data archive services. (Data products are described in greater detail in the GPM Data Products section.)

The PPS will reside at the NASA Goddard Space Flight Center. Additional data processing systems are envisioned at JAXA's Earth Observation Research and application Center (EORC) and ESA's European Space Research Institute (ESRIN) in Tokyo, Japan and Frascatti, Italy, respectively. Each of these will make important contributions to the overall GPM mission.

GPM Validation Program

GPM is attempting to make the most comprehensive and accurate measurements of global precipitation is ever obtained. As noted previously, precipitation is an extremely rapidly varying meteorological variable in both space and time. Therefore, an extensive network of ground validation (GV) sites is needed. No single nation can practically set up and maintain, or for that matter pay for, such a network. Just as with the space hardware, an international collaboration is needed for these validation activities. The main functions of the GPM GV program will be: 1) to acquire ground-based sensor data relevant to the validation of and/or comparison with satellite sensor measurements and standard precipitation product retrievals; and 2) to produce, archive, and publicly make available on the Internet standard GV products. The program has three main objectives:

- Determine the measurement uncertainty for GPM measurements to allow users of GPM data to interpret results with proper caution and restraint;

- Improve the retrieval algorithms used by GPM and future space-based precipitation measurement missions; and

- Improve the ground-based GV measurements themselves, which have historically been beset with difficulties.

The GPM GV program will consist of a worldwide network of GV measuring sites—referred to as 'GPM GV Sites'—and their associated scientific and technical support organizations. The sites will be distributed all across the globe and each will represent their own self-interests and concerns, but will all operate under a straightforward strategy. They all agree to serve the greater GPM community by engaging in various means to communicate their scientific findings. Beyond that, however, the individual GPM GV sites have a great deal of flexibility as to how they run their operation, what types of instrumentation they use, and so forth.

To assure a degree of consistency across the eventual site network, a subset of the GPM GV sites will be designated 'GV Supersites', which will operate in a semi-continuous, near-realtime mode under a well-defined GV data reporting protocol supported by the GSFC PPS. GV Supersites will, in addition to their normal activities, provide near-realtime error characteristics concerning instantaneous rain rate retrievals from the core-level satellites (i.e., Core and EGPM), consisting of bias, bias uncertainty, and spatial error covariance information. They will also support ongoing standard algorithm improvement by reporting significant errors in instantaneous retrievals from the core-level satellites to scientific groups authoring and maintaining the standard rain rate algorithms, including with the reports, essential core (and core type) satellite and GV data needed to effectively interpret algorithm breakdowns.

GPM Principal Scientific Themes

As a means to achieve the scientific objectives of the GPM Mission, various scientific strategies have evolved within the different NASA, JAXA, and ESA Science Teams that will accomplish the majority of the initial research. NASA has chosen to divide the research process into different themes, emphasizing the fundamental barrier problems. Thus, for NASA's GPM Scientific Implementation Plan (GPM SIP) there are nine principal research themes which help organize the research and guide the evolution of the research working groups. These nine themes and main topic areas for research are as follows:

1. Global Water and Energy Cycle Processes and Modeling: Role of Precipitation

2. Climate System Variability and Climate Diagnostics: Role of Precipitation

3. Climate Model Simulations and Reanalysis, NWP Techniques, and Data Assimilation: Role of Precipitation

4. Land Surface Hydrology and Hydrometeorological Modeling: Role of Precipitation

5. Ocean Surface and Marine Boundary Layer Processes: Role of Precipitation

6. Coupled Cloud-Radiation Modeling: Physical Interpretation of Precipitation Processes

7. Precipitation Retrieval:
   a. Reference Radar-Radiometer Core Algorithm/Radar Simulator Studies
   b. Parametric Radiometer Constellation Algorithm/Radiometer Simulator Studies
   c. Cross-Satellite Calibration Transfer and Bias Removal

8. Calibration and Validation of Satellite Precipitation Measurements

9. Applications, Public Service and Educational Outreach

GPM Partners

GPM represents the largest international cooperative effort on a satellite mission to date. NASA and JAXA will lead the mission and coordinate overall development, operations, and research activities. Other partners participate in their selected areas, which includes hardware (spacecraft, instrument, launch vehicle, and launch operations), ground systems development (flight operations system, science data processing, and archive and distribution system), system operations (flight operations, launch operations. and science system operations), data validation, and research activities.

Besides overall management and leadership, NASA is contributing two spacecraft (Core and Constellation), two identical passive microwave radiometers, launch services for Constellation, the ground system, and PPS. NASA will also contribute to and participate in algorithm development and data validation activities. JAXA plans to contribute DPR, the launch vehicle, and launch operation services, and participate in algorithm development and data validation activities.

The Goddard Earth Sciences Distributed Active Archive Center (GDAAC) receives data from all members of the federation and creates data products. Besides the GDAAC, the Global Hydrology Climate Center (Huntsville, Alabama), the JAXA data processing center (Japan), and other partner data centers are involved. These other centers generate products and send them to the GDAAC.

GPM Instruments

The objectives of GPM require that two types of measurements be made: near-global measurements of rainfall and three-dimensional measurements of cloud structure and precipitation (including drop size distributions). These measurements can best be obtained using two different types of instruments: a PMW radiometer, the GMI, and an active radar, the DPR.

GMI

GPM Microwave Imager—NASA

Microwave radiometers are versatile instruments, and when properly configured, they can be used to infer a wide variety of phenomena, such as atmospheric moisture and temperature profiles, soil moisture, and sea surface temperature. Their versatility has made them instruments of choice for a variety of measurement programs, including environmental remote sensing and weather forecasting. Plans are in place to use microwave radiometers on several satellite missions that will be in orbit during the GPM era. GPM has initiated the planning and coordination needed so that the measurements made by these instruments will be available to assist GPM in meeting its objectives for frequent, global measurements of rainfall.

GMI is a conical-scan, passive microwave radiometer that will be used for rainfall measurement. NASA will procure two nearly identical GMI instruments from industry, one instrument to be placed on Core, and the other on Constellation. Although the vendor for GMI has not been selected at this time, the instrument's design will most likely incorporate substantial heritage from a previous design (see Key GMI Facts). This heritage will benefit GPM by reducing the technical risk, time required for design and fabrication, and procurement cost. GMI will be designed to make simultaneous measurements in several microwave frequencies (e.g., 10.7, 19.3, 21, 37, 89 GHz), giving the instrument the capability to measure a variety of rainfall rates and related environmental parameters. Additional, higher frequency measurement channels (150–165 and 183 GHz) are under consideration in order to provide increased sensitivity for the measurement of light rains frequently found at Earth's higher latitudes; a decision concerning the inclusion of these additional measurement channels will be made as part of the procurement process.

The notional design for GMI includes an offset parabolic reflector of approximately 1.0 m diameter that rotates about the instrument's vertical axis. The antenna will point at an off-nadir angle of ~49º, providing a ground measurement swath of ~850 km from side-to-side centered along the ground-track of the core spacecraft. The speed of rotation has not been firmly established, but most heritage systems have used a rotational rate of about 32 rpm. During each 2-s revolution, measurements will be made over ~130º scan sector centered on the spacecraft velocity vector. The remaining 230º of the antenna rotation will be used to perform a hot and a cold calibration and other housekeeping functions. The instrument will thus be calibrated once per scan at both ends of its measurement range, or about every two seconds. The rotating mass of the instrument generates momentum that must be compensated either by the instrument or by the spacecraft. Momentum compensation can be incorporated into the instrument, accomplished by a separate wheel placed on the spacecraft, or assumed by the spacecraft attitude control system; a decision concerning which approach will be used has not been identified at this time. The GMI is expected to

Key GMI Facts

Heritage: TRMM Microwave Imager (TMI), Special Sensor Microwave Imager (SSM/I), Special Sensor Microwave Imager/Sounder (SSMIS), Conical Scanning Microwave Imager/Sounder (CMIS)

Instruments: Two identical instruments, one for Core spacecraft and one for NASA Constellation spacecraft.

Instrument Type: Passive Microwave Radiometer

Scan Type: Conical scan at off-nadir angle of ~49º

Swath: 850 km from side to side centered along the spacecraft ground track.

Spectral Range: 10.65–89.0 GHz (possibly up to 183 GHz)

Channels: 10.65 GHz, H & V Pol; 18.7 GHz, H & V Pol; 21.3 GHz, V Pol; 37.0 GHz H & V Pol; 89.0 GHz, H & V Pol. Additional higher frequency channels at 150–165 and 183 GHz are also under consideration.

Dimensions: Electronics enclosure: 0.5 m × 0.5 m × 0.5 m; antenna size: ~1.0 m diameter

Mass: 100 kg

Power: 90 W

Data Rate: 14 kbps

Calibration: Hot and cold calibration once per scan at both ends of the GMI measurement range, about every two seconds

Contributor: TBD; NASA will conduct competitive procurement from industry

Key DPR Facts

Heritage: Precipitation Radar (PR) on TRMM

Instrument Type: Active Radar

Swath: 245 km (comprised of 49 footprints, each 5 km in width)

Mass: 660 kg

Power: 570 W

have mass of about 70 kg. The electronics enclosure should be on the order of 0.5 m × 0.5 m × 0.5 m, supporting the ~1.0 m diameter reflector.

DPR

Dual-frequency Precipitation Radar—JAXA

Detailed measurements of cloud structure and precipitation characteristics will be made with the DPR. JAXA is providing this instrument for GPM. The DPR is comprised of two essentially independent radars operating in the microwave region of the electromagnetic spectrum. One radar operates in the Ku-Band (13.6 GHz) and is referred to as the Precipitation Radar (PR)-U. The other radar operates in the Ka-Band (35.55 GHz) and is referred to as the PR-A. By measuring the reflectivities of rain at two different radar frequencies, it is possible to infer information regarding rainrate, cloud type and its three-dimensional structure, and drop-size distribution.

The design approach for both radars is based upon the TRMM PR design, updated as necessary to incorporate new technologies, and modified for operation at the specified frequencies. Like the PR, each of the DPRs uses a 128-element active phased array. The two radars are designed to provide temporally matching ground footprints with the same spatial size and scan pattern. Careful physical alignment of the radar antennas will be required on the spacecraft to ensure that co-alignment of the beams is achieved on-orbit. The DPR will have a 245 km wide ground swath, comprised of 49 footprints, each 5 km in width. The DPR's mass is estimated to be 660 kg. The antenna for PR-U will be 2.4 m × 2.4 m × 0.5 m in size, and that for PR-A will be 1.0 m × 1.0 m × 0.5 m.

GPM References

Adams, W. J., P. Hwang, D. Everett, G. M. Flaming, S. Bidwell, E. Stocker, J. Durning, C. Woodall, and T. Rykowski, 2002: Global Precipitation Measurement—Report 8: White Paper, W. J. Adams and E. A. Smith, eds., NASA STI Program Office, 31 pp. NASA/TM—2002-211609

Smith, E., and 31 others, 2005: International Global Precipitation Measurement (GPM) Program and Mission: An Overview, Measuring Precipitation from Space: EURAINSAT and the Future, Kluwer Publishers, in press.

Key DPR Facts *(cont.)*

Data Rate: 190 kbps

Consists of two distinct radar systems:

Precipitation Radar-A (PR-A)
- Frequency: 35.55 GHz
- Sensitivity: 11 dBZ
- Peak Power: 180 W
- Antenna Size: 1.0 m × 1.0 m × 0.5 m

Precipitation Radar-U (PR-U)
- Frequency: 13.6 GHz
- Sensitivity: 17 dBZ
- Peak Power: 1000 W
- Antenna Size: 2.4 m × 2.4 m × 0.5 m

Contributor: JAXA

GPM Data Products

All routine swath and gridded products will be archived and distributed by the Goddard Earth Sciences Distributed Active Archive Center (GDAAC). Products are generated through three levels. Level 1 consists of the calibrated, geo-located, instrument values at the instrument field of view. Level 2 maintains the instrument footprint orientation but converts instrument values to physical parameters, the key parameter for GPM being precipitation rate. Level 3 products aggregate the Level 2 physical parameters into different time-space grid orientations. This level provides the key climate quality research products produced by GPM.

Product Name or Grouping	Processing Level	Coverage	Spatial/Temporal Characteristics
GMI and DPR			
Calibrated Geo-located Instrument Values[2]	1	Instrument Field-of-View or Footprint	Raw instrument data
Physical Parameters[2]	2	Instrument Field-of-View or Footprint	The key parameter for the mission is precipitation rate
Climate Research Quality Product[2]	3	Global	Accuracy is stressed over timeliness
Global Precipitation Map[1]	3	Global	Global precipitation map available to all via the internet in near real time
Global Precipitation Product[1]	3	Global	Product to be used in weather modeling and forecast improvement; available every three hours.

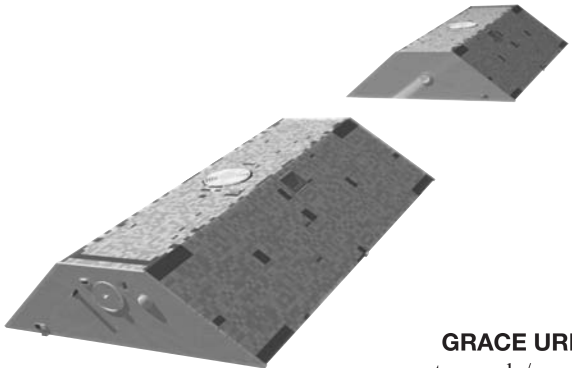
[1] All data are made available to designated users 20 minutes after the collection of the last data bit in the product.

[2] All data are made available to designed users within 48 hours of having received all necessary data input.

GPM Data Products

GRACE

Gravity Recovery and Climate Experiment



GRACE URL
www.csr.utexas.edu/grace

Summary

The GRACE mission enables the most precise measurements of Earth's mean and time-variable gravity field ever obtained and should lead to advances in the fields of hydrology (continental and regional water balance, monitoring changes in aquifers), oceanography (studying ocean currents, ocean heat flux, ocean bottom pressure, sea-level rise), and solid-Earth sciences.

Instruments

- Black-Jack Global Positioning System Receiver (GPS)
- High Accuracy Inter-satellite Ranging System (HAIRS)
- Star Camera Assembly (SCA)
- SuperStar Accelerometer (SSA)
- Ultra Stable Oscillator (USO)

Note: Unlike most missions, the twin GRACE satellites are not platforms for independent remote-sensing instruments. Instead, the satellites themselves act in unison as the primary science instrument. Listed here as 'instruments' are the components needed to make gravity measurements.

Points of Contact

- *GRACE Principal Investigator:* Byron Tapley, University of Texas Center for Space Research (UTCSR)

- *GRACE German Co-Principal Investigator:* Christoph Reigber, GeoForschungsZentrum Potsdam (GFZ)

- *GRACE Project Scientist:* Michael M. Watkins, NASA Jet Propulsion Laboratory/California Institute of Technology

Key GRACE Facts

Joint with Germany

Heritage: Challenging Minisatellite Payload (CHAMP)

Platform: Carbon fiber reinforced plastic layered aluminum honeycomb main equipment panel for μm-level dimensional stability

Orbit:

Type: 500 km near-circular polar orbit at launch, w/220 ± 50 km separation between the satellites
Altitude: 500 km
Inclination: 89°
Period: 94.417 minutes at launch
Repeat Cycle: None, track evolves naturally

Dimensions: Twin trapezoid satellites, 3.1 m × 0.8 m × (1.9–0.7) m each

Mass: Each satellite weighs 460 kg

Power: 160 W (94 W payload and s/c; 56 W heaters)

Fuel: 34 kg GN2 propellent for attitude control and station-keeping

Design Life: Planned five-year mission

Average Data Rate: 1 Mbps

Data Relay Methods: Weilheim & Neustrelitz stations—German Space Operations Center (GSOC)

Downlink: S-Band

Transmission Frequency: 24 and 32 GHz for K-Band ranging

Thermal Control: 0.1° C on critical components

Attitude Control: Star sensor, Gyro, Magnetometer, Mag-torquer, GN2 thrusters

Pointing: 3–5 mrad dead-band pointing of K-band horn to other GRACE satellite

Accuracy of Calibrations:

K-Band Horn Alignment: Known to within 0.02° of Star Camera

Accelerometer Alignment: Known to within 0.03° of Star Camera

Satellite Center of Gravity: Measured and actively trimmed to within 20–40 μm of the center of the accelerometer

Other Key Personnel

- *GRACE Program Scientist:* John LaBrecque, NASA Headquarters
- *GRACE Program Executive:* Lou Schuster, NASA Headquarters
- *GRACE Project Manager:* Joseph Beerer, NASA Jet Propulsion Laboratory/California Institute of Technology

Mission Type

Earth Observing System (EOS) Exploratory Mission (Earth System Science Pathfinder)

Launch

- *Date and Location:* March 17, 2002, from Plesetsk Cosmodrome, Russia
- *Vehicle:* Rockot launch vehicle

Relevant Science Focus Areas

(see NASA's Earth Science Program section)

- Climate Variability and Change
- Earth Surface and Interior
- Water and Energy Cycles

Related Applications

(see Applied Sciences Program section)

- Disaster Management
- Water Management

GRACE Science Goals

- *Primary goal:* Provide global, high-resolution estimates of the constant and time-variable part of Earth's gravity field, with unprecedented accuracy.
- *Secondary goal:* Measure several hundred global atmospheric profiles per day to determine how GPS measurements are distorted by Earth's atmosphere and ionosphere.

Background

Measurements of Earth's gravity field provide integral constraints on the distribution of mass within the Earth system. A record of time variations in Earth's gravity field reflects the exchange of mass (primarily from moving water) within the land, ocean, and atmosphere components of the Earth system. Such records serve as important global constraints on the models of variability and exchange within and between each sub-system. The mean Earth

Key GRACE Facts *(cont.)*

Satellite Subsystems

Responsible Center: NASA JPL

Satellite System: Astrium Space (Germany)

Attitude Control System: Space Systems/Loral (U.S.)

Instrument Subsystems

Responsible Center: NASA JPL

GPS: NASA JPL

HAIRS: NASA JPL

Microwave Assembly: Space Systems/Loral (U.S.)

Star Cameras: Danmarks Tekniske Universitet (Technical University of Denmark)

SuperStar Accelerometer: Office National d'Etudes et de Recherches Aerospatiale (ONERA) (France)

Ultra Stable Oscillator: Applied Physics Laboratory (Johns Hopkins University) (U.S.)

Launch & Ground Operations

Responsible Center: Deutches Zentrum für Luft und Raumfahrt (DLR) (Germany)

Launcher Subsystem: Eurockot GmbH (Germany)

Mission Operations: German Space Operations Center (GSOC)

Science Data System

Responsible Centers: UTCSR, NASA JPL, GFZ gravity field, on the other hand, provides constraints on the composition and structure of the Earth. In addition, over the oceans, it provides the reference surface relative to which ocean topography variations and ocean currents and their changes may be reckoned. Precise gravity field measurements, therefore, in conjunction with other satellite and in situ measurements, underpin a large variety of climate-change-related studies in oceanography, hydrology, glaciology, and solid-Earth sciences (see NRC 1997 for a survey of applications).

Past determinations of Earth's gravity field have used a combination of multi-decadal records of space-based satellite tracking data as well as land and marine gravity measurements. The satellite tracking data have contributed primarily to the determination of the long- and medium-wavelength static gravity field—whereas terrestrial data have determined the medium and short wavelengths. Determinations of the variability of Earth's gravity field however, have been limited in the past to only the very longest wavelengths—a combination of lack of coverage as well as limited precision of tracking. For these reasons, the need for global, high-resolution and accurate measurements of Earth's gravity field for Earth system science has long been articulated.

GRACE is a joint NASA-DLR Earth gravity-field-mapping mission, implemented under the Earth System Science Pathfinder Program starting in 1997. The change in distance between the twin co-orbiting GRACE satellites (popularly named Tom and Jerry) is used, along with ancillary data, to monitor the mean and time-variable gravity field of Earth.

Using the GRACE Satellites as an Instrument to Measure Gravity

With the GRACE mission, the spatio-temporal variations of Earth's gravity field are traced by a sequence of estimates of the spherical harmonic coefficients of the geopotential model. While Earth's gravity has a continuum spectrum of variability, for reasons of limitations of ground-track-coverage density, this spectrum is represented by a set of monthly piece-wise constant estimates of the parameters of the Earth gravity model. The monthly gravity-field estimate is obtained from a continuous record of change in the distance between the twin GRACE satellites.

Spatial and temporal variations in Earth's gravity field affect the orbits (or trajectories) of the twin spacecraft slightly differently. These differences are manifested as changes in distance between the spacecraft as they orbit Earth. This change in distance is reflected in the change in time-of-flight of microwave signals transmitted and received nearly simultaneously between the two spacecraft. While this differential orbital motion is considerably smaller than the gross motion of any one satellite, having a pair of co-orbiting satellites makes it possible to measure continuously and with high precision, these minute changes in distances. Designed at JPL, the High Accuracy Inter-satellite Ranging System (HAIRS) provides this distance change as phase change of the microwave carrier signals. Measurements are made at 24 and 32 GHz to correct for the ionospheric effects on the signal. The dual one-way range (or its numerical derivatives) can be reconstructed from these phase

GRACE Instruments

GPS
Global Positioning System

Provides digital signal processing; measures the change in distance relative to the GPS satellite constellation.

HAIRS
High Accuracy Inter-satellite Ranging System

K-band microwave ranging system that provides precise (within 10 μm) measurements of the change in distance between the two satellites—these measurements are used to infer changes in gravity.

SCA
Star Camera Assembly

Precisely determines satellite orientation by tracking the satellite relative to the position of the stars.

SSA
SuperStar Accelerometer

Precisely measures the non-gravitational accelerations acting on the satellite.

USO
Ultra Stable Oscillator

Provides frequency generation for the K-band ranging system.

data using precise relative timing between the satellites obtained from simultaneous GPS tracking data. Precision of such distance-change measurements is a few µm, over a nominal separation distance of 220 km.

Since the range change depends not only on the gravity field, but also on non-gravitational force variations, each satellite carries the SuperSTAR Accelerometer (SSA). Built by ONERA (France), this accelerometer uses the principle of electrostatic levitation to suspend a proof-mass within an electrostatic cage. The cage itself is rigidly attached to the GRACE spacecraft and is affected by the skin forces acting on the satellite. The proof-mass is located at the center of gravity of the spacecraft and is in free-fall so that non-conservative forces cause the distance between the proof-mass and the electrode cage to change continuously. This distance is measured using capacitive sensors and is used to derive the control forces necessary to keep the proof-mass centered within the cage. These control forces are therefore a measure of the non-gravitational forces acting on the satellite.

The GRACE satellites also carry a geodetic quality, BlackJack GPS receiver, which provides the precise relative and absolute timing for the data, as well as the absolute position of the spacecraft. The dual star cameras (SCA) are used to obtain the precise orientation of the spacecraft, in particular for the accelerometer and the K-Band boresight.

Unlike most remote-sensing-instrument suites or missions, the science product from the GRACE mission itself is not a sequence of quasi-instantaneous and independent images of Earth. The GRACE products are not a sequence of images or time slices of a particular process or state variable, but rather continuous records of the time history of the motion of the twin satellites. The suite of GRACE satellite measurements—primarily the range change, the non-gravitational acceleration vector, and the precise pointing – is collected over a suitably large span of time. This is to ensure sufficient density of data coverage either globally or regionally. For global models, sufficient density of coverage— required to support determination of gravity fields to a few 100 km resolution—is obtained in approximately one month. This data set is then used in conjunction with a variety of ancillary data to provide an estimate of the average state of Earth's gravity field over that month.

The GRACE products are defined to be the coefficients of a spherical harmonic model of Earth's gravity field. Each month, a set of harmonics complete to degree and order 100 is reported (approximately 400-km effective wavelength). In addition, a long-term mean to degree and order 160 is to be provided.

Using GRACE GPS Receivers as Atmospheric Limb Sounders

Although GRACE is primarily an experiment to measure gravity, the extremely precise GPS receivers onboard can also be used as atmospheric limb sounders. Limb sounding involves scanning across the atmosphere (called Earth's limb) and can be used to measure how much a radio wave (a GPS signal) is distorted as it travels through Earth's atmosphere and ionosphere. (This is analogous to what happens to a beam of light when it passes through water.) The precise degree of bending depends on the atmospheric conditions—pressure, temperature, and moisture content—and on the density of electrons in the ionosphere.

Distortions caused by the atmosphere remain constant with changing radio frequencies but ionospheric distortions vary depending on the radio frequencies. So, by varying the radio frequency, it is possible to distinguish how much of the distortion is caused by the atmosphere and how much is caused by the ionosphere. So using this technique, it is possible to ascertain profiles of pressure, temperature, and humidity for the atmosphere and also to measure the variability of electron density in the ionosphere.

The limb technology on GRACE extends and complements other spaceborne atmospheric sensors. GRACE will provide about 500 limb sounding measurements per day, unaffected by weather conditions (such as clouds and storms) that hinder or block other satellite sensors. The GRACE limb sounding measurements will help determine the effectiveness of limb sounding as a cost effective means of improving numerical weather prediction. It will also help to advance our understanding of the Sun's influence upon Earth's environment, including its effects on climate, weather, radar, and radio communications. Limb sounding will also be studied as a means of detecting rapid vertical changes of Earth's surface such as volcanic explosions, earthquakes, tsunamis, and other such phenomena, which are thought to cause disturbances in the ionosphere.

Data Products

The Science Data System is responsible for system development, data processing, and archiving. The GRACE Raw Data Center (RDC) at DLR in Neustrelitz, Germany receives the telemetry data. NASA JPL handles Level 1 data processing, where sensor calibration factors are applied, the data are correctly time-tagged, quality control flags are added, and the data sample rate is reduced from the high rate data of previous levels. Data are then sent to UTCSR and GFZ, where the mean and time variable gravity field is derived from calibrated and validated data. Data are archived for distribution at JPL's Physical Oceanography Distributed Active Archive Center (PO.DAAC) and at GFZ's Information System and Data Center (ISDC). GRACE data include 30-day estimates of gravity fields, as well as profiles of air mass, density, pressure, temperature, water vapor, and ionospheric electron current.

GRACE References

Dunn, C. E., and 19 others, 2003: Instrument of GRACE: GPS augments gravity measurements, application challenge. *GPS World*, **14 (2)**, 16–28.

National Research Council, 1997: *Satellite Gravity and the Geosphere: Contributions to the Study of the Solid Earth and Its Fluid Envelope*, National Academy Press, Washington D.C.

Tapley, B. D., S. Bettadpur, J. C. Ries, P. F. Thompson, M. Watkins, 2004: GRACE measurements of mass variability in the Earth system. *Science*, **305**, 503–505.

Tapley, B. D., S. Bettadpur, M. M. Watkins, and C. Reigber, 2004: The Gravity Recovery And Climate Experiment: Mission overview and early results. *Geophys. Res. Lett.*, **31**, L09607, doi:10.1029/2004GL019920.

Tapley, B. D., S. Bettadpur, M. Cheng, D. Hudson, and G. Kruizinga, 2003: Early results from the Gravity Recovery And Climate Experiment. Paper AAS-03-622, AAS/AIAA Astrodynamics Specialists Conference, Big Sky, Montana.

Watkins, M. M., and S. Bettadpur, 2000: The GRACE Mission: Challenges of using micron-level satellite-to-satellite ranging to measure the Earth's gravity field. *Proc. Internat. Symposium on Space Dynamics*, Biarritz, France 26–30 June 2000, Centre national D'Etudes Spatiales (CNES), Delegation a la Communication.

Watkins, M. M., E. S. Davis, W. G. Melbourne, T. P. Yunck, J. Sharma, S. Bettadpur, and B. D. Tapley, 1995: GRACE: A new mission concept for high resolution gravity field mapping. *Proc. Euro. Geophys. Soc.*, Hamburg, Germany.

GRACE Data Products

Product Name or Grouping	Processing Level	Coverage	Spatial/Temporal Characteristics
GRACE *Data Set Start Date: April 14, 2002*			
Intersatellite Range (and Derivatives)	1B	Continuous	5 s
Non-Gravitational Accelerations	1B	Continuous	1 s
Attitude (Quaternions)	1B	Continuous	5 s
GPS Tracking	1B	Continuous (L1/L2, P1/P2 & CA)	1–10 s
Monthly Geopotential	2	Global (~30 days)	Harmonic degree 100 (max)
Mean Geopotential	2	Global (lifetime)	Harmonic degree 160 (max)

Notes:

Level 1B Products are the processed range and acceleration measurements, which are input to Level 2 processing while creating the gravity field.

Level 2 Products are monthly models for the Earth gravity field (derived from Level 1B data products and ancillary data).

L1/L2 refers to the phase at the two GPS frequencies; P1/P2 refers to the precise (P) code tracking; CA is an acronym for Coarse-Acquisition code tracking.

GRACE Data Products

ICESat

Ice, Cloud and land Elevation Satellite

ICESat URL
icesat.gsfc.nasa.gov/

Key ICESat Facts

Orbit:
Type: Near polar, low-Earth orbit
Altitude: ~600 km
Inclination: 94°
Period: ~97 minutes
Repeat Cycle: 91 days with ~33 days subcycle

Dimensions: Approximately 2.2 m × 1.0 m × 1.5 m, solar panel area is ~8 m^2

Mass: ~950 kg total

Power: ~330 W (GLAS)

Downlink: X-Band and S-Band radio-frequency channels

Design Life: 3 years

Summary

ICESat provides primarily ice sheet and sea ice altimetry products with secondary products being cloud/aerosol and land/vegetation data. In particular, the mission determines variations of ice sheet elevation through time over Greenland and Antarctica, altitude and thickness of clouds and aerosol layers, vegetation, land topography, and ocean surface and sea ice altimetry.

Instrument

- Geoscience Laser Altimeter System (GLAS)

Points of Contact

- *ICESat Project Scientist:* H. Jay Zwally, NASA Goddard Space Flight Center
- *ICESat Science Team Leader:* Bob E. Schutz, University of Texas-Austin

Other Key Personnel

- *ICESat Program Scientist:* Craig Dobson, NASA Headquarters
- *ICESat Program Executive:* Lou Schuster, NASA Headquarters

Mission Type

Earth Observing System (EOS) Systematic Measurements

Launch

- *Date and Location:* January 12, 2003, shared launch with the Cosmic Hot Interstellar Plasma Spectrometer (CHIPS), from Vandenberg Air Force Base, California
- *Vehicle:* Delta II rocket

Relevant Science Focus Areas

(see NASA's Earth Science Program section)

- Climate Variability and Change
- Earth Surface and Interior
- Water and Energy Cycles

Related Applications

(see Applied Sciences Program section)

- Air Quality
- Carbon Management
- Coastal Management
- Ecological Forecasting
- Water Management

ICESat Science Goals

- Provide repeated, precision, polar ice sheet elevations through time for improved mass-balance measurements
- Provide atmosphere-cloud heights and aerosol distribution data
- Provide land topography and vegetation cover data

ICESat Mission Background

GLAS is an advanced, high-precision, solid-state, neodymium:yttrium-aluminum-garnet (Nd:YAG) laser altimeter. It has three lasers to improve the reliability for meeting its planned multi-year mission, but only one laser is operational at any given time. GLAS uses integral star trackers and gyros for determination of precise laser orientation and GPS for precise position determination; this is augmented by ground-based-satellite laser ranging. Data from the components of GLAS are combined to provide Earth elevation data with a precision of 10 cm or better per laser pulse.

The mission's science objectives are repeated, precision, ice sheet elevation data that will enable improved mass-balance estimates for Greenland and Antarctica. In addition, as the GLAS instrument produces 532-nm (visible) as well as 1064-nm (near-infrared) wavelength pulses, it provides cloud and aerosol information that is not available from passive sensors, especially of the layering structure through the atmosphere. The temporal and spatial extent of clouds common to polar areas that may impact the ice sheet measurements is also being determined. Finally, the third science objective of the ICESat mission, collection of land-topography data, is being achieved by processing the continuously operating laser-altimeter data throughout its global orbit.

ICESat began its science mission on February 20, 2003. It is now orbiting with the GLAS instrument operating for specific periods.

GLAS

Geoscience Laser Altimeter System

GLAS has three lasers, with only one laser operating at any given time. Precision orbital and pointing knowledge is obtained via redundant GPS units, a gyro system, a laser reference system, and instrument- and spacecraft-mounted star trackers, supported by ground-based laser ranging. GLAS includes the Stellar Reference System, which consists of a charge-coupled device (CCD) camera system to determine the direction of the laser beam with respect to the stars and also with respect to the GLAS optical bench.

The ICESat mission measures ice sheet topography and associated temporal changes, cloud and atmospheric properties, and along-track topography over land and water. For ice sheet applications, the laser altimeter effectively measures the distance from the spacecraft to the ice sheet, to a precision of better than 10 cm with a laser surface-spot size of ~70 m every ~170 m. The distance measurement, coupled with knowledge of the radial orbit position and the direction of the laser beam in space, enables the precise determination of surface topography. Characteristics of the return pulse are used to determine surface roughness. Changes in ice sheet thickness even of a few tens of centimeters provide information needed for improved ice sheet mass balance estimates and support prediction analyses of cryospheric response to climatic changes. The ice sheet mass balance and contribution to sea-level change will also be determined over the mission lifetime. The accuracy of height determinations over land is assessed using ground slope and roughness data. Along-track cloud- and aerosol-height distributions are determined with a vertical resolution of ~75 m. The horizontal resolution of ICESat's cloud data varies from 175 m for dense clouds to 50 km for the thinnest aerosol structure and planetary boundary layer height. Unambiguous measurements of cloud height and the vertical structure of thin clouds support studies on

Key GLAS Facts

Heritage: MOLA

Instrument Type: A three-laser system, with a single laser operating at any given time

Scan Type: Nadir Viewing

Dimensions: Telescope diameter is 1 m, instrument height is ~175 cm

Mass: 300 kg

Power: 330 W average

Data Rate: ~450 kbps

Specifications:

	Surface	Atmosphere
Wavelengths	1064 nm	532 nm
Laser Pulse Energy	74 mJ	30 mJ
Laser Pulse Rate	40 Hz	40 Hz
Laser Pulse Width	5 nsec	5 nsec
Telescope Diameter	1.0 m	1.0 m
Receiver FOV	0.5 mrad	0.16 mrad
Receiver Optical Bandwidth	0.8 nm	0.03 nm
Detector Quantum Efficiency	30%	60%
Detection Scheme	Analog	Photon Counting
Vertical Sampling Resolution	0.15 m	75 m
Surface Ranging Accuracy (single pulse)	< 10 cm/pulse	
Laser Pulse Pointing Knowledge	< 2 arcsec	

Uses: Nd:YAG laser with 1.064- and 0.532-μm output

Primary cloud and aerosol data are extracted from the green pulse

Height Measurements: Determined from the round-trip pulse time of the infrared pulse the influence of clouds on radiation balance and climate feedbacks. Polar clouds and haze are detected and sampled with much greater sensitivity, vertical resolution, and accuracy than can be achieved by passive sensors. Planetary boundary layer height is directly and accurately measured for input into surface-flux and air-sea and air-land interaction models. Direct measurements of aerosol vertical profiles contribute to understanding of aerosol-climate effects and aerosol transport.

The GLAS instrument was developed by a NASA GSFC led instrumentation team, and the ICESat spacecraft was supplied by Ball Aerospace. GLAS uses a diode-pumped, Q-switched Nd:YAG laser with energy levels of approximately 75 mJ (1.064 µm) and 35 mJ (0.532 µm). Three lasers are included, but only one laser operates at a time. The pulse repetition rate is 40 pulses/s, and the beam divergence is approximately 0.11 mrad. The echo pulses are collected in a 1-m-diameter telescope. The infrared pulse is used for surface altimetry and some cloud measurements, and the green pulse is primarily used for measurements of thin clouds but is also used for aerosol measurements.

The Stellar Reference System (SRS), which is part of the GLAS instrument, supports determination of the laser-pointing direction in space with a precision of about 1.5 arcsec. SRS consists of several CCD cameras: an Instrument Star Tracker (IST), a Laser Reference System (LRS), and a Laser Profile Array (LPA). SRS is an innovative instrument developed at GSFC. IST obtains 10-Hz images of the star field in the instrument zenith direction with an 8° field of view, and LRS includes a 10-Hz, 0.5° field of view of the stars that overlaps with IST. LRS also captures an image of the transmitted 1064-nm laser pulse and an image of a collimated reference source mounted on IST. LPA also images the transmitted laser pulse, but the imaging is performed at 40 Hz.

GLAS URL

glas.gsfc.nasa.gov/

ICESat References

Algorithm Theoretical Basis Document References available at: www.csr.utexas.edu/glas/atbd.html.

GLAS Science Team: Geoscience Laser Altimeter System GLAS: Science Requirements, Version 2.01, October 1997.

ICESat Brochure available at: icesat.gsfc.nasa.gov/publicoutreach.htm.

Zwally, H. J., B. Schutz, W. Abdalati, J. Abshire, C. Bentley, *et al.*, 2002: ICESat's laser measurements of polar ice, atmosphere, ocean, and land. *J. Geodyn.*, **34**, 405–445.

Key GLAS Facts *(cont.)*

Spatial Resolution: At 40 pulses per second, the centers of 70-m spots are separated in the along-track direction by 170 m for a 600-km altitude orbit; the cross-track resolution is determined by the ground-track repeat cycle and orbit control.

Duty Cycle: 100%

Thermal Control: Radiators, heat pipes, supplemented by heaters

Thermal Operating Range: 20° ± 5° C

Telescope FOV: Nadir only, 375 µrad and 160 µrad (0.532 µm)

Instrument IFOV: ~70 m laser footprint at nadir

Pointing Requirements (platform + instrument):

Control (3σ): 30 arcsec roll, 30 arcsec pitch, 1° yaw.

Post-processed pointing knowledge (1σ): 1.5 arcsec (roll and pitch axes, provided by instrument-mounted star trackers, gyro system, and Stellar Reference System.

Post-processed position requirements: Radial orbit for ice sheet to <5 cm and along-track/cross-track position to <20 cm (to be provided by spacecraft-mounted GPS receiver and SLR array).

Orbit repeat tracks: The ICESat orbit is controlled so that its ground track is maintained within 800 m at the equator of a specified reference (ideal) ground track and to ~100 m over polar ice.

Off-nadir pointing: ICESat enables off-nadir pointing of the laser up to 5° to enable repeat ground tracks at approximately 100 m and to point at targets of opportunity, including calibration targets; in the polar regions, the GLAS laser is always pointed at the reference ground track to support repeat-track analysis.

Reference orbit: ICESat uses two reference ground tracks: an 8-day repeat track and a 91-day repeat track. The 91-day repeat track has an approximately 33-day subcycle, which provides a nearly uniform distribution of tracks with a 30-km separation between tracks in the same direction at the equator.

ICESat Data Products

ICESat data can be accessed at: nsidc.org/data/icesat.

Product Name or Grouping	Processing Level	Coverage	Spatial/Temporal Characteristics
GLAS *Data Set Start Date: February 20, 2002*			
Global Altimetry Data	1A	Global	70 m footprint sampled at 170 m spacing, vertical resolution 3 cm
Global Atmosphere Data	1A	Global	40 km vertical coverage sampled at 170 m spacing, vertical resolution 76 m
Global Engineering Data	1A	Global	Sampled once every 4 seconds
Global Laser Pointing Data	1A	Global	Sampled at 40 Hz and 10 Hz
Global Waveform-based Range Corrections Data	1B	Global	70 m footprint sampled at 170 m spacing, vertical resolution 3 cm
Global Elevation Data	1B	Global	70 m footprint sampled at 170 m spacing, vertical resolution 3 cm
Global Backscatter Data	1B	Global	40 km vertical coverage sampled at 170 m spacing, vertical resolution 76 m
Global Planetary Boundary Layer and Elevated Aerosol Layer Heights	2	Global	40 km vertical coverage sampled at 170 m spacing, vertical resolution 76 m
Global Heights for Multi-layer Clouds	2	Global	40 km vertical coverage sampled at 170 m spacing, vertical resolution 76 m
Global Aerosol Vertical Structure Data	2	Global	40 km vertical coverage sampled at 170 m spacing, vertical resolution 76 m
Global Cloud/Aerosol Optical Depths Data	2	Global	40 km vertical coverage sampled at 170 m spacing, vertical resolution 76 m
Antarctic and Greenland Ice Sheet Altimetry Data	2	Global	70 m footprint sampled at 170 m spacing, vertical resolution 3 cm
Sea Ice Altimetry Data	2	Global	70 m footprint sampled at 170 m spacing, vertical resolution 3 cm
Global Land Surface Altimetry Data	2	Global	70 m footprint sampled at 170 m spacing, vertical resolution 3 cm
Ocean Altimetry Data	2	Global	70 m footprint sampled at 170 m spacing, vertical resolution 3 cm

ICESat Data Products

Jason

Jason URLs
sealevel.jpl.nasa.gov/mission/jason-1.html
www.aviso.oceanobs.com/

Key Jason Facts

Joint with France

Orbit
Type: Circular, non-sun-synchronous
Descending Node: N/A
Altitude: 1336 km
Inclination: 66º
Period: 112.4 minutes
Repeat Cycle: 9.9156 days

Dimensions:
Satellite support module: 95.4 cm × 95.4 cm × 100.0 cm
Payload module 95.4 cm × 95.4 cm × 121.8 cm
Solar array span: Two wings with four 1.5 m × 0.8 m panels per wing; total surface of 9.8 m^2

Mass: 500 kg

Power: 2100 W

Downlink: Jason telemetry downlink is 0.7 Mbps (700 Kbps) S-Band to JPL, Wallops Island, Virginia, Poker Flats, Alaska, and Aussaguel, France

Design Life: 3-year primary mission; 2-year extended mission

Contributors: NASA, CNES

Summary

Jason maps ocean surface topography. The data collected provide information on ocean surface current velocity and heights which, when combined with ocean models, can lead to a four-dimensional description of ocean circulation. Data from Jason are also extending ocean surface topography into the 21st century, providing a 5-year view of global ocean surface topography, increasing understanding of ocean circulation, improving forecasting of climate events, and measuring global sea-level change.

Instruments

- Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS)
- Jason Microwave Radiometer (JMR)
- Laser Retroreflector Array (LRA)
- Poseidon-2 altimeter
- Turbo Rogue Space Receiver (TRSR), a Global Positioning System (GPS) receiver

Points of Contact

- *NASA Jason Project Scientist:* Lee-Lueng Fu, NASA Jet Propulsion Laboratory/California Institute of Technology
- *CNES Jason Project Scientist:* Yves Menard, Centre National d'Etudes Spatiales (CNES) Toulouse Space Center

Other Key Personnel

- *Jason Program Scientist:* Eric Lindstrom, NASA Headquarters
- *Jason Program Executive:* Lou Schuster, NASA Headquarters
- *Jason Project Manager:* Sophie Coutin-Faye, CNES Toulouse Space Center
- *Jason Mission Operations Manager:* Mark Fujishin, NASA Jet Propulsion Laboratory/California Institute of Technology
- *Jason Mission Operations Manager:* Nathalie Malechaux, CNES Toulouse Space Center

Mission Type

Earth Observing System (EOS) Systematic Measurements

Launch

- *Date and Location:* December 7, 2001, from Vandenberg Air Force Base, California
- *Vehicle:* Delta II rocket

Relevant Science Focus Areas

(see NASA's Earth Science Program section)

- Climate Variability and Change
- Water and Energy Cycles

Related Applications

(see Applied Sciences Program section)

- Coastal Management
- Disaster Management

Jason Science Goals

- Determine general ocean circulation and understand its role in Earth's climate, particularly how ocean circulation impacts Earth's hydrological and biogeochemical cycles.

- Study the variation of ocean circulation, on time scales ranging from seasonal and annual to decadal, and how this variation impacts climate change.

- Collaborate with other global ocean-monitoring programs to produce routine models of the global ocean for scientific and operational applications.

- Study large-scale ocean tides.

- Study geophysical processes and their effects on ocean surface topography.

Jason Mission Background

To gather useful long-term information about Earth's oceans and currents, orbiting instruments must take extremely precise measurement of the topography of the ocean surface. Ocean surface topography measurements determine the height of the ocean surface relative to a hypothetical ocean surface that corresponds to mean sea level in the absence of winds, currents, and most tides—called Earth's 'geoid'. Such measurements should not be confused with bathymetry measurements, which are used to map the topography of the ocean bottom. Ocean surface topography data have significant practical applications including in the study of global climate and weather, monitoring of shoreline evolution, protection of ocean fisheries, and other operational oceanographic efforts.

Ocean topography measurements also help scientists determine important characteristics of ocean circulation. For example, the 'surface geostrophic current' is an important measurement for ocean circulation studies. Scientists are particularly interested in measuring the surface geostrophic current because it can indicate something about the density of water in the deep ocean. Scientists can combine the information on ocean surface topography with measurements of ocean density from other sources, and by doing so they can obtain a picture of the ocean circulation throughout the entire water column of the ocean.

Ocean topography measurements can also be used to measure the heat content of the ocean. Most of the heat stored in Earth's hydrosphere resides in the ocean. The top 3 m of the ocean surface contain as much heat energy as the heat energy stored by all of Earth's atmosphere. This enormous amount of heat is distributed around the world by ocean currents and has a profound influence

Jason Instruments

DORIS

Doppler Orbitography and Radiopositioning Integrated by Satellite

DORIS is a precision orbit-determination system that provides orbital positioning information. An onboard receiver accurately measures the Doppler shift on both transmitted frequencies (401.25 MHz and 2,036.25 MHz) received from an Orbit Determination Beacon (ODB) station.

JMR

Jason-1 Microwave Radiometer

JMR is a three-frequency microwave radiometer that measures total water vapor along the path viewed by the altimeter and is used for range correction. It measures brightness temperatures in the nadir column at 18.7, 23.8, and 34 GHz.

LRA

Laser Retroreflector Array

LRA is used to calibrate the other location systems on the satellite with a very high degree of precision. LRA is a totally passive reflector designed to reflect laser pulses back to their point of origin on Earth. It consists of nine suprasil quartz retroreflectors arranged to provide a near-hemispherical response.

Poseidon-2

Poseidon-2 is a dual-frequency radar altimeter that maps the topography of the sea surface and can be used for calculating ocean surface current velocity; it also measures ocean wave height and wind speed.

TRSR

Turbo Rogue Space Receiver

TRSR is a high-performance GPS receiver designed to provide tracking data for precise orbit determination of the Jason spacecraft. It measures precision GPS code phase and continuous carrier phase data from up to 12 GPS satellites.

on Earth's climate and on climate variability. Ocean topography measurements provide a means of monitoring the movement of heat energy in the oceans from space.

Jason provides global sea-surface-topography measurements and is a follow-on to the highly successful TOPEX/Poseidon mission, which was launched in 1992 and ceased operations in October 2005, after nearly 62,000 orbits. Jason assumed the orbit of TOPEX/Poseidon, which moved into a parallel orbit. While Jason and TOPEX/Poseidon were both flying in this tandem formation, the science return was doubled. The primary instrument on Jason is Poseidon-2, a solid-state altimeter. The altimeter instrument suite includes the Jason Microwave Radiometer (JMR), which at the time of launch was a technologically new instrument. JMR uses monolithic microwave integrated circuitry (MMIC) technology and weighs an order of magnitude less than the radiometer on TOPEX/Poseidon. The Precision Orbit Determination package includes the GPS receiver, TRSR, DORIS, and a Laser Retroreflector Array.

The Poseidon-2 altimeter on Jason provides high-precision measurements of sea surface topography in one dimension. It makes measurements along the track of the spacecraft—called an 'along-track measurement'. This means that the geostrophic velocity (or geostrophic current) of the ocean is also computed in one dimension. The geostrophic velocity is measured in the direction perpendicular to the ocean topography measurement and thus cuts across the track of the spacecraft—called a 'cross-track measurement'.

At each point where the ascending and descending tracks of the spacecraft intersect—called a 'crossover point'—scientists can obtain two cross-track measurements. This allows them to determine the two-dimensional velocity of the current at that point. Once they know the velocity of the current at a particular location, they can then measure the 'Reynolds stress' at the same location. Reynolds stress is an important parameter in ocean circulation studies that describes the forces imposed on the mean ocean flow by turbulent fluctuations—called 'eddies'. Reynolds stress possesses the largest share of the ocean kinetic energy and is responsible for transfer of momentum, energy, heat, salt, and other biogeochemical properties of the ocean. Accurate measurements of Reynolds stress are therefore needed to understand the dynamics of ocean general circulation.

Key DORIS Facts

Heritage: SPOT-2, TOPEX/Poseidon, SPOT-3, SPOT-4, Envisat

Instrument Type: Precision Orbit Determination System

Dimensions:

- Receiver: 32 cm × 27 cm × 10 cm
- Ultra Stable Oscillator (USO): 9 cm × 7 cm × 12 cm
- USO Shielding: 33 cm × 29 cm × 10 cm
- Antenna: 37 cm height × 16 cm diameter cone

Mass:

- Receiver: 5.6 kg
- USO: 1.2 kg
- USO Shielding: 8 kg
- Antenna: 2 kg
- Total: 17 kg (Dual-string configuration)

Power: 21 W

Duty Cycle: 100%

Data Rate: 330 bps

Thermal Control: Heat transfer by conduction to mounting surface and by radiation within the instrument module

Thermal Operating Range: -10° to 50° C

FOV: 125° cone (centered on nadir)

Pointing Requirements (platform + instrument, 3σ):

- Control: 1.5°
- Knowledge: 0.2° (depending on the distance between the antenna phase center and the satellite center of mass)

Contributors: CNES (Responsible center), THALES (Instrument), SMP (Ground beacons)

Key JMR Facts

Heritage: TOPEX/Poseidon, Seasat, Nimbus-7

Instrument Type: Three-channel microwave radiometer

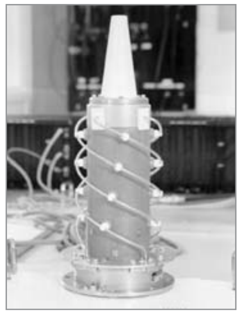
Scan Type: Fixed pencil-beam spatially collocated with the nadir-pointing Poseidon altimeter beam

Channel Center Frequencies: 18.7, 23.8, and 34.0 GHz

Channel Bandwidths: 200, 400, and 700 MHz

DORIS

Doppler Orbitography and Radiopositioning Integrated by Satellite



DORIS is based on the accurate measurement of the Doppler shift of radiofrequency signals transmitted from ground-based beacons and received onboard the spacecraft when it passes over. Measurements are made at two frequencies: 2.03625 GHz for precise Doppler measurement and 401.25 MHz for ionospheric correction. The 401.25 MHz measurement is also used for time tagging and auxiliary data. Approximately 60 global all-weather radio beacons are currently in operation.

The separation of the two transmitting frequencies makes it possible to reduce the ionospheric effect to around the 1 cm level. Tropospheric refraction is modeled using surface meteorological data that are directly transmitted to the satellite from the ground stations.

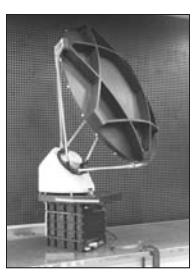
DORIS was validated by a prototype flown on the Systeme pour l'Observation de la Terre-2 (SPOT-2) satellite, launched in 1990. It provides over six-thousand measurements per day, which are used to refine data-processing methods and to improve models of Earth's gravity field. Another DORIS instrument flies on the TOPEX/Poseidon spacecraft launched in 1992. An improved DORIS instrument flew on SPOT-4 (launched in 1998) and added the ability to perform onboard orbit determination. The DORIS instrument on Jason incorporates these new capabilities. Experience with SPOT-2, SPOT-4, and TOPEX/Poseidon has shown that the instrument operates most efficiently at an altitude between 750 and 1,500 km. However, DORIS can operate at altitudes from 300 km to several thousand km.

DORIS URL

www.jason.oceanobs.com/html/doris/welcome_uk.html

JMR

Jason Microwave Radiometer



JMR provides an estimate of radar path delay due to tropospheric water vapor in a beam collocated with that of the Poseidon-2 nadir altimeter—a dual-channel (C- and Ku-band), nadir-looking radar altimeter that measures range to the ocean surface. This nadir altimeter range measurement, along with precise orbit determination (POD) of the spacecraft position relative to the Earth geoid, yields

Key JMR Facts *(cont.)*

Antenna Half-Power Beamwidth: 1.8°, 1.5°, and 0.9°

Dimensions:
- Antenna: 0.79-m offset feed parabola
- Envelope including reflector: 130 cm × 80 cm × 70 cm
- Electronics module: 25 cm × 25 cm × 25 cm

Mass: 27 kg

Power: 31 W

DC Supply Bus: Unregulated 23–36 V

Data Rate: 1024 bps

Thermal Control: Electronics thermal control provided by spacecraft using radiative coupling. Thermal control on the JMR is achieved by radiating out to the satellite structure. The JMR box is internally mounted, with no direct exposure to space.

Thermal Operating Range: 10° to 35° C

Radiometric Resolution: < 0.25 K

Absolute Calibration Accuracy: ±1K

System Noise Temperature: < 650 K

Contributors: NASA JPL (responsible center, instrument design), TRW (receiver units)

Key LRA Facts

Heritage: TOPEX/Poseidon

Function: Laser-tracking targets

Wavelengths: 532 nm (primary), 1064 nm (secondary)

Configuration: 9 corner cubes: 1 nadir looking, 8 arrayed azimuthally in truncated cone

FOV: 110º w/1.5 arcsec dihedral angle per cube

Dimensions: Each cube is 163-mm diameter × 66-mm height

Mass: 0. 8 kg

Duty Cycle: 100%

Thermal Operating Range: -65º to 95º C

Contributors: NASA (responsible center), ITE Inc. (instrument) ocean height. To meet ocean-height-accuracy requirements, however, the radar altimeter range measurements must be corrected for path delay due to ionosphere, dry air in the atmosphere, and tropospheric water vapor.

An estimate of integrated free-electron content using the difference in time of flight between the two nadir radar frequencies provides the ionosphere-delay correction. The dry atmosphere delay can be estimated from widely available global surface barometric pressure data. The delay due to water vapor is determined using measurements from the three-channel microwave radiometer. The apparent increase in path length due to water vapor typically ranges from 5–10 cm in cold dry air, to 30–50 cm under warm, humid conditions.

The JMR instrument measures single polarization, radiometric brightness temperature in three channels optimized for downward looking water-vapor retrieval over the ocean. These include a 23.8-GHz channel, the primary water-vapor sensor, an 18.7-GHz channel to estimate ocean-surface contributions to the observed brightness temperature, and a 34.0-GHz channel to estimate cloud liquid. An antenna-pattern correction is applied to the resulting measurements to correct for brightness-temperature contributions from outside the main beam, and a retrieval algorithm using empirically derived coefficients yields the wet-path-delay estimate for altimeter range correction. The overall error budget allocation for the JMR water-vapor correction is 1.2 cm.

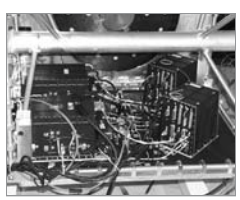
The Jet Propulsion Laboratory, in Pasadena, California, has overall responsibility for JMR management, system design, electronics development, integration and test, and calibration. The MMIC receiver modules were developed by TRW, Inc. in Redondo Beach, California. The JMR includes, as part of its heritage, radiometers flown aboard the Nimbus-7, Seasat, and TOPEX/Poseidon spacecraft.

JMR URL

sealevel.jpl.nasa.gov/technology/instrument-radiometer.html

LRA

Laser Retroreflector Array



The LRA is one of three location systems on board Jason—the three systems are used together to measure the satellite's position on orbit. The ability to determine a satellite's precise position on orbit is critical in interpreting altimetry data used for measuring ocean surface topography.

The LRA is used to calibrate the other Jason location systems and to verify the altimeter's height measurements. The LRA is an array of mirrors onboard the satellite that provides a target for laser-tracking measurements from ground stations. By analyzing the round-trip time of the laser beam, it is possible to determine precisely where the satellite is on its orbit. The laser-tracking data

Key Poseidon-2 Facts

Heritage: Poseidon-1 radar altimeter (TOPEX/Poseidon)

Instrument Type: Dual-frequency radar Altimeter (Ku-band and C-band)

Scan Type: Fixed nadir-pointing beam

Transmitted Pulse Width: 105 s

Pulse Repetition Frequency: 2100 Hz (1800 Hz for Ku-band and 300 Hz for C-band)

Maximum Radio-Frequency Output

Power to Antenna: 38.5 dBm (Ku-band); 44 dBm (C-band)

Transmission Frequency: 13.575 GHz (Ku-band), 5.3 GHz (C-band)

Dimensions:

Radio Frequency Unit (RFU): 42.2 cm × 24.6 cm × 24.5 cm

Power Control (PC) Unit: 26.8 cm × 20.5 cm × 24.9 cm

Mass: 52 kg (dual-frequency, dual configuration with one antenna)

Power: 66 W

DC Supply Bus: Unregulated 21–32 V

Duty Cycle: 100%

Data Rate: 22.5 kbps (including waveform data and onboard estimated parameters)

Thermal Control: Heat transfer by conduction to mounting surface and by radiation within the instrument module

Thermal Operating Range: -5° to 35° C

Pointing Requirements (platform + instrument, 3σ):

Control (Satellite): 0.33°

Knowledge: < 0.1°

Contributors: CNES (responsible center), Alcatel Space Industries (prime contractor) are analyzed to calculate the satellite's altitude to within a few mm; however, because there are a small number (10–15) of ground stations and the laser beams are sensitive to weather conditions, it is not possible to track the satellite continuously using the LRA alone. That is why other location systems are needed on board the satellite.

Jason's LRA consists of nine quartz corner-cube reflectors arrayed on a circular structure on the satellite's nadir side (facing Earth). A corner-cube reflector is a special type of mirror that always reflects an incoming light beam back in the direction from which it came. The retroreflectors are optimized for a wavelength of 532 nm (green), providing a field of view of about 100°.

The LRA was manufactured by ITE, Inc., for NASA Goddard Space Flight Center.

LRA URL

sealevel.jpl.nasa.gov/technology/instrument-lra.html

Poseidon-2

Poseidon-2 is a nadir-looking radar altimeter that maps the topography of the sea surface. The shape and strength of the radar-return pulse also provide measurements of ocean-wave height and wind speed, respectively. Through the mapping of sea surface topography, Poseidon-2 provides information on the ocean surface current velocity which, when combined with ocean models, can lead to a four-dimensional description of ocean circulation. The heat and biogeochemical fluxes carried by ocean currents hold the key to understanding the ocean's role in global changes in climate and biogeochemical cycles. Secondary research contributions include the study of the variations in sea level in response to global warming/cooling and hydrological balance, the study of marine geophysical processes (such as crustal deformation) from the sea surface topography, and the monitoring of global sea state from the wave-height and wind-speed measurement.

Poseidon-2 was designed by Alcatel Space Industries (ASPI) for CNES Toulouse Space Center, and is essentially an improved version of the Poseidon-1 altimeter that flies on TOPEX/Poseidon (see TOPEX/Poseidon description). Poseidon-2 improves on Poseidon-1 by adding a second frequency at 5.3 GHz, changing to digital technology, and using a new more powerful rad-hard microprocessor. It makes these improvements while keeping the same compact mass and size as its predecessor.

Poseidon-2 URL

www.aviso.oceanobs.com/html/missions/jason/instruments/poseidon2_uk.html

Key TRSR Facts

Heritage: Blackjack GPS receiver (Shuttle Radar Topography Mission)

Instrument Type: GPS Receiver and Antenna

Dimensions:
- Receiver: 18 cm × 18 cm × 11 cm
- Antenna: 10.5-cm height × 30-cm diameter

Mass:
- Receiver: 2.5 kg
- Antenna: 0.855 kg
- Total: 6.5 kg (Dual-string configuration)

Power: 14W @ 28 V

Duty Cycle: 100%

Data Rate: 800 bps

Thermal Control: Heat transfer by conduction to mounting surface and by radiation within the instrument module

Thermal Operating Range: -10° to 50° C

Pointing Requirements:
- Control: 5°
- Knowledge: 5°

Contributors: NASA JPL (responsible center); Spectrum Astro (instrument)

TRSR

Turbo Rogue Space Receiver

The ability to determine Jason's precise position in orbit is critical to interpreting its altimetry data. The TRSR is one of three location-determination systems onboard Jason that are used to measure the satellite's position. The TRSR uses the Global Positioning System (GPS) constellation of navigation satellites for this purpose.

The TRSR concurrently tracks the radio signals transmitted by up to 12 GPS satellites. The receiver measures the phase of the GPS carrier signals with better than 1-mm precision and measures the pseudo-range between Jason and each GPS spacecraft being tracked with better than 10-cm precision. (Pseudo-range is a measurement of the transit time of the signal between satellites. The measurement contains timing errors, which can later be corrected to recover the true range.) The TRSR's measurements determine the satellite's position in near-real time to better than 20 m and its clock to better than 100 nsec. There are two complete and independent TRSR systems onboard Jason.

To achieve the orbit accuracy goals, detailed knowledge of the Jason spacecraft and its behavior need to be known so the forces acting on the spacecraft can be modeled. In ground processing, the TRSR's GPS observables will enable determination of the Jason orbit height with an accuracy of 1–2 cm.

TRSR measurements of variations in Jason's orbital motion in relation to Earth's center will improve our overall knowledge of Earth's gravity field. NASA's Jet Propulsion Laboratory, at the California Institute of Technology, designed and tested the TRSR hardware, software, and ground-support. Spetrum Astro. Inc fabricated the TRSR flight unit.

TRSR URL

sealevel.jpl.nasa.gov/technology/instrument-gps.html

Jason References

Carayon, G., N. Steunou, J.-L. Courriere, and P. Thibaut, 2003: Poseidon-2 radar altimeter design and results of in-flight performances. *Marine Geodesy*, **26**, 159–165.

Chelton, D. B., J. C. Ries, B. J. Haines, L-L. Fu, and P. S. Callahan, 2001: Satellite altimetry, in L-L. Fu and A. Cazenave, eds., *Satellite Altimetry and Earth Sciences*, Academic Press, San Diego, 1–131.

Fu, L-L., and D. Chelton, 2001: Large scale ocean circulation, in L-L. Fu and A. Cazenave, eds., *Satellite Altimetry and Earth Sciences*, Academic Press, San Diego, 133–169.

Ménard, Y., L-L. Fu, P. Escudier, F. Parisot, J. Perbos, P. Vincent, S. Desai, B. Haines, and G. Kunstmann, 2003: The Jason-1 mission. *Marine Geodesy*, **26**, 131–146.

Perbos, J, P. Escudier, F. Parisot, G. Zaouche, P. Vincent, Y. Menard, F. Manon, G. Kunstmann, D. Royer, and L.-L. Fu, 2003: Jason-1: Assessment of the system performance. *Marine Geodesy*, **26**, 147–157.

Vincent, P., S. D. Desai, J. Dorandeau, M. Ablain, B. Soussi, P. S. Callahan, and B. J. Haines, 2003: Jason-1 geophysical performance evaluation. *Marine Geodesy*, **26**, 167–186.

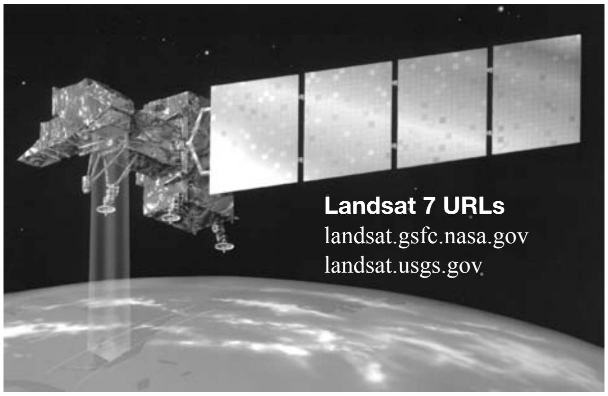
Jason Data Products

Additional information can be found at: podaac.jpl.nasa.gov

Product Name or Grouping	Processing Level	Coverage	Spatial/Temporal Characteristics
DORIS, JMR, LRA, Poseidon-2, TRSR *Data Set Start Date: January 15, 2002*			
Operational Sensor Data Record (DORIS, JMR, Poseidon-2)	2	Global	66° N – 66° S latitude/every 10 days
Interim Geophysical Data Record (DORIS, JMR, LRA, Poseidon-2)	2	Global	66° N – 66° S latitude/every 10 days
Geophysical Data Record (GDR)	2	Global	66° N – 66° S latitude/every 10 days
Near-Real-Time Sea Surface Height Anomaly (DORIS, JMR, LRA, Poseidon-2, TRSR)	2	Global	66° N – 66° S latitude/every 10 days
Sea Surface Height Anomaly (SSHA) (DORIS, JMR, LRA, Poseidon-2, TRSR)	2	Global	66° N – 66° S latitude/every 10 days
Gridded Sea Surface Height Anomaly (DORIS, JMR, LRA, Poseidon-2, TRSR)	2	Global	66° N – 66° S latitude/every 10 days

Jason Data Products

Landsat 7



Key Landsat 7 Facts

Joint with U.S. Geological Survey (USGS)

Heritage: Landsat 4, 5

Orbit:
- Type: Circular, sun-synchronous
- Equatorial Crossing: 10:00 a.m. ± 15 mins
- Altitude: 705 km ± 5 km (at the equator)
- Inclination: 98.2° ± 0.15°
- Period: 98.9 min
- Repeat cycle: 16 days/233 orbits

Dimensions: 4 m high, 2.7 m diameter

Mass: 1982 kg

Power: 1550 W

Downlink: Three 150 Mbps wideband downlinks

Antennas: 3 gimbaled X-band, 2 omni S-band

Design Life: 5 years

Partners

Spacecraft: Lockheed Martin

ETM+: Raytheon Santa Barbara Remote Sensing

Data Archival, Processing, Ground Operations: USGS National Center for Earth Resources Observation System (EROS) data center

Spacecraft and Sensor Maintenance: NASA GSFC

Calibration: EROS and GSFC

Summary

July 23, 2002, was the 30th anniversary of the launch of the first of a series of Landsat satellites that have continuously supplied the world with global land surface images. Landsat 5, launched in 1984, continues to provide important observations of the landmass of the planet and has established a record for reliability in the civilian satellite fleet. Landsat 7 joined Landsat 5 in April 1999. Both Landsat 5 and Landsat 7 provide data for remote sensing and Geographic Information System (GIS) science and applications around the world. NASA was responsible for the development and launch of Landsat 7 and the development of the ground system. USGS is responsible for operating the satellite, distributing the data, and maintaining an archive of Landsat 7 and other remotely sensed data.

Instrument

- Enhanced Thematic Mapper Plus (ETM+)

Points of Contact

- *Project Scientist:* Darrel Williams, NASA Goddard Space Flight Center
- *Deputy Project Scientist:* James Irons, NASA Goddard Space Flight Center

Other Key Personnel

- *Landsat 7 Program Scientist:* Garik Gutman, NASA Headquarters
- *Landsat 7 Program Executive:* Lou Schuster, NASA Headquarters

Mission Type

Earth Observing System (EOS) Systematic Measurements

Launch

- *Date and Location:* April 15, 1999, from Vandenberg Air Force Base, California
- *Vehicle:* Delta II

Relevant Science Focus Areas

(see NASA's Earth Science Program section)

- Carbon Cycle, Ecosystems, and Biogeochemistry
- Earth Surface and Interior

Related Applications

(see Applied Sciences Program section)

- Agricultural Efficiency
- Air Quality
- Aviation
- Carbon Management
- Coastal Management
- Disaster Management
- Ecological Forecasting
- Energy Management
- Homeland Security
- Invasive Species
- Public Health
- Water Management

Landsat 7 Science Goals

- Acquire sunlit, essentially cloud-free global seasonal coverage of Earth's land masses.
- Provide well-calibrated radiometric and geometric data.
- Provide imagery that are sufficiently consistent in terms of acquisition geometry, spatial resolution, spectral characteristics, and calibration with previous Landsat data to meet requirements for global-change research.

Landsat Chronology

The first Landsat, originally named the Earth Resources Technology Satellite (ERTS-1), was developed by NASA and launched in July 1972. Subsequent first generation Landsat launches occurred in January 1975 and March 1978. In the meantime, a second generation of Landsat satellites was developed. Landsat 4 was launched in July 1982 and Landsat 5 in March 1984. Images are still being received from Landsat 5. As a result, a continuous set of Landsat remotely sensed images of Earth's land surface and surrounding coastal regions from mid-1972 until the present is available.

Over the past 32 years, scientists have developed a wide range of applications using Landsat imagery for global-change research, regional environmental studies, national security, and other civilian and commercial purposes. For example, Landsat images have been used to monitor agricultural productivity, urban growth, and land-cover change, and are used widely for oil, gas, and mineral exploration. Other science applications include monitoring volcanoes, glacier dynamics, forestation/deforestation, and coastal conditions.

Authorized by Public Law 102-555 in October 1992, Landsat 7 continues the long-standing Landsat tradition. The science mission of Landsat 7 is targeted to regional and global assessments of land-cover dynamics. The mission has generated and is periodically refreshing a global archive with substantially cloud-free, sunlit imagery. For the first time, a Long-Term Acquisition Plan was devised to ensure maximal global data acquisition, taking into account vegetation seasonality and cloud cover. This ensures a data archive recording the full seasonal and interannual changes in the vegetation patterns of the planet, while minimizing the effects of cloud cover. In addition, the seasonal requirements of various science-community niches such as reefs and glaciers have been incorporated into the acquisition plan.

While NASA's other EOS instruments, like the Moderate Resolution Imaging Spectroradiometer (MODIS) and Multi-Angle Imaging SpectroRadiometer (MISR), acquire frequent, coarser views of land-cover change, the higher spatial resolution of ETM+ data from Landsat 7 allows researchers to determine the actual causes of observed land-cover changes. These changes have important implications, both for local habitability and for the global cycling of carbon, nitrogen, and water.

In 1994, management of the Landsat Program was assigned jointly to NASA, NOAA, and the USGS. In March 1999, this management structure was streamlined to include NASA and USGS only. NASA was responsible for the development and launch of

Key ETM+ Facts

Instrument Type: Imaging radiometer

Scan Type: Whiskbroom scanning radiometer

Calibration: Full-aperture solar calibrator, partial-aperture solar calibrator, internal calibration lamps for reflective bands; blackbody source for thermal band

Field of View (FOV): ±7.5°; 183 km

Instrument Instantaneous FOV (IFOV):
Bands 1–5, 7: 42.5 ±4.3 μrad
Panchromatic Band (8):
19.5 μrad × 21.5 μrad
Thermal Band (6): 85.0 ±9 μrad

Swath: 183 km, ±7.5°

Repeat Cycle: 16-day

Spectral Range and Spatial Resolution:

7 reflective spectral bands, including:
- Three 30 m visible (VIS) bands
- One 30 m near infrared (NIR) band
- Two 30 m shortwave infrared (SWIR) bands
- One 15 m panchromatic (PAN) band
- One emissive 60 m thermal infrared (TIR) band

Dimensions:
Scanner Assembly: 196 cm × 114 cm × 66 cm
Auxiliary Electronics: 90 cm × 66 cm × 35 cm

Mass: 425 kg

Power: 590 W (imaging), 175 W (standby)

Duty Cycle:
16.7% imaging over 23 hours
131 min within 600 min sliding window
52 min within 200 min sliding window
34 min within 100 min sliding window
15 min night imaging per orbit

Data Rate: 150 Mbps over two 75-Mbps channels (I and Q)

Thermal Control: 90 K radiative cooler

Real-time Data: Yes

Date of Initial Data Acquisition:

April 18, 1999 (all data prior to June 29, 1999 are engineering data; science data are available starting June 29, 1999, when the ETM+ was declared operational) the Landsat 7 satellite and the development of the ground system. USGS is responsible for operating the satellite, distributing the data, and maintaining an archive of Landsat 7 and other remotely sensed data.

With Landsat 5 recently surpassing 20 years of continuous operation on orbit, Landsat 7 provides much-needed continuation of land remote-sensing data critical to understanding environmental change and supports a broad range of other important Earth science and Earth resource applications.

Landsat 7 Program Objectives

- Maintain Landsat data continuity by providing imagery that is consistent in terms of acquisition geometry, spatial resolution, calibration, coverage characteristics, and spectral characteristics, and calibration with previous Landsat imagery.

- Generate and periodically refresh a global archive of substantially cloud-free sunlit land-mass imagery.

- Continue to make Landsat-type data available to U.S. and international users at the cost of fulfilling user requests, and expand the use of such data for global-change research and commercial purposes.

Landsat 7 Flight Segment

The Landsat 7 satellite consists of a spacecraft bus and a single instrument, the Enhanced Thematic Mapper Plus (ETM+). Like its predecessors, Landsat 7 produces Landsat scenes based on the Worldwide Reference System, consisting of 57,784 scenes, each 183 km × 170 km. Approximately 15,000 of these cover the land-mass, coastal and island scenes of the world that are emphasized in the Long-Term Acquisition Plan developed for Landsat 7. The Landsat 7 satellite operates in a circular, sun-synchronous orbit with an inclination of 98.2°, an altitude of 705 km, and a descending-node equatorial crossing time of 10:00 a.m. ±15 minutes. This orbit allows Landsat 7 to precede the Terra satellite by 30 minutes along a common ground track. The common orbit with Terra offers additional opportunities for data fusion with the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), MISR, and MODIS sensors. The 183-km swath of coverage provided by the ETM+ field-of-view makes it possible to view any given point on the globe once every 16 days.

The ETM+ instrument is an improved version of the Thematic Mapper instruments that flew on Landsat 4 and 5. Like the earlier instruments, ETM+ acquires data for six visible, near-infrared, and shortwave infrared spectral bands at a spatial resolution of 30 m. The ETM+ instrument also incorporates a 15-m-resolution panchromatic band as well as improved ground resolution for the thermal infrared band (60 m vs. 120 m). Incorporation of in-flight full- and partial-aperture solar calibration has improved the overall radiometric accuracy to better than 5%. ETM+ provides imagery that is sufficiently consistent in terms of acquisition geometry, spatial resolution, spectral characteristics, and calibration with previous Landsat imagery to meet requirements for global change research.

A state-of-the-art solid-state recorder capable of storing 380 Gbits of data (100 scenes) is used to store selected scenes from around the world for playback over the U.S. ground station at EROS in Sioux Falls, South Dakota. Data are also routinely downlinked to a station in Australia and forwarded by tape to EROS. Additional U.S. ground stations in Alaska, Svalbard, Norway, and McMurdo, Antarctica are used for special operations. In addition, real-time data from ETM+ are also transmitted to cooperating international ground stations and U.S. ground stations on command.

Landsat 7 Ground Segment

The ground system includes the spacecraft Mission Operations Center built by NASA at Goddard Space Flight Center (GSFC) in Greenbelt, Maryland, and operated by USGS. This Landsat-7-unique facility, augmented by other existing NASA institutional facilities, is utilized to control all spacecraft and instrument operations for the life of the mission. Flight operations are controlled from GSFC with commands uplinked via the Landsat Ground Station in Sioux Falls and via NASA's Tracking and Data Relay Satellite System (TDRSS).

In addition to the Mission Operations Center, NASA built all data processing and distribution components of the Landsat 7 system. These components were integrated into EROS in South Dakota. After launch and on-orbit activation and verification of the satellite and data processing and distribution components, the data processing, archiving, and distribution portions of the ground system were turned over by NASA to USGS for operation. Since then, USGS has re-engineered the ground system to create a multi-mission facility capable of supporting data reception from Landsat 5 and 7, Terra and Earth Observing-1 (EO-1), as well as archiving, processing and distributing products from the entire historical Landsat archive.

In addition to the data reception, processing and archiving functions, NASA and the USGS developed an Image Assessment System (IAS) located at EROS. The IAS continually collects data on the ETM+ radiometric and geometric performance, providing NASA and USGS scientists with a plethora of information and statistics used to monitor the quality and consistency of the data going into the national archive. This capability has been key in Landsat 7's unparalleled achievements in data characterization and calibration—hallmarks in the success of the mission.

Landsat 7 scientific data are processed and distributed by EROS. The ground system at EROS is capable of capturing and processing at least 250 Landsat scenes per day to Level 0R (no radiometric calibration, limited geometric correction) and delivering at least 100 scenes to users each day. Scenes are processed to Level 1 (radiometric and geometric corrections applied) at user requests.

Landsat 7 imagery are available for ordering within 24 hours after they are received at EROS. Users query metadata and browse images to determine if the archive contains data files suitable for their use. Data requested can be delivered either electronically or in a digital format on CD-ROM by common carrier.

ETM+

Enhanced Thematic Mapper Plus

An 8-band imaging radiometer aimed at providing high spatial resolution, multispectral images of the sunlit land surface, using visible, near-infrared, shortwave infrared, and thermal infrared wavelength bands, along with a panchromatic band. It is an enhanced version of the Thematic Mapper (TM) onboard earlier Landsat satellites.

Landsat 7 ETM+ Anomaly (May 2003)

The ETM+ sensor performed flawlessly for over four years, acquiring more than 550,000 digital image scenes of Earth's land mass. However, on May 31, 2003 a component of ETM+, known as the scan line corrector (SLC), malfunctioned. By mid-July 2003 the ETM+ resumed its global land survey mission resulting in only a six-week gap of imagery in the U.S. archive. However, the malfunction has had an impact on the imagery from Landsat 7.

The ETM+ optics contain the Scan Mirror and Scan Line Correction Assembly among other components. The Scan Mirror provides the across track motion for the imaging, while the forward velocity of the spacecraft provides the along track motion. The Scan Line Correction Assembly (SLC) is used to remove the 'zig-zag' motion of the imaging field of view produced by the combination of the along and across track motion. Without a functioning SLC, the ETM+ line of sight now traces a zig-zag pattern across the satellite ground track (Fig. 1).

In this SLC-off mode, the ETM+ still acquires approximately 78% of the desired data for any given scene. The gaps in data form alternating wedges that increase in width from the center to the edge of a scene (Fig. 2).

The remainder of the ETM+ sensor, including the scanning mirror, continues to operate, radiometrically and geometrically, at the same high-level of accuracy and precision as it did before the anomaly; therefore, image pixels are still accurately geolocated and calibrated.

The Landsat 7 ETM+ system continues to produce high-quality data of the Earth's land areas. To fulfill the expectations of the user community for full coverage of single scenes, data from multiple acquisitions are being merged to resolve the SLC-off data gaps. The first of these gap-filled products was released from EROS in May 2004. In this Phase I release, the gaps in a current SLC-off scene are filled with data from a SLC-on scene that was acquired approximately one year earlier (i.e., during the same plant phenological stage). The two scenes are geometrically registered, and a histogram-matching technique is applied to the fill pixels that provide the best-expected radiance values for the missing data. The new product represents an effort by the USGS Landsat 7 Project at the EROS Data Center in Sioux Falls, South Dakota to increase the utility of the Landsat 7 ETM+ data affected by the non-functional SLC.

The Phase II release occurred in November 2004 and contained a more advanced product that merged data from multiple SLC-off scenes acquired within weeks of each other. In all cases, a binary bit mask is provided so that the user can determine where the data for any given pixel originated. The USGS is continuing to research other methods of providing better merged data products, and will continue to provide information resulting from this work as it becomes available.

Further information and product samples of the new gap-filled Landsat 7 data can be found at: landsat.usgs.gov/slc_enhancements/gapfilled1.php.

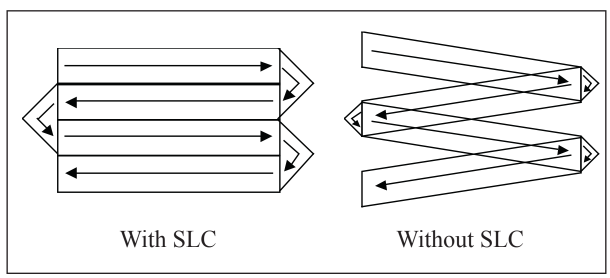


Figure 1

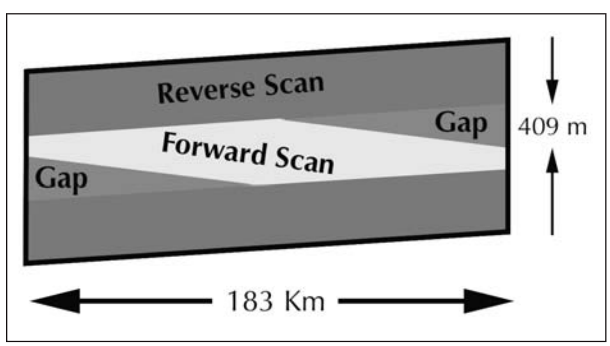


Figure 2

For information on all Landsat data products, visit the Landsat Data Products web site at: landsat.usgs.gov/dataprod.php.

Landsat 7 References

Goward, S. N., and D. L. Williams, 1997: Landsat and Earth systems science: Development of terrestrial monitoring. *Photogram. Eng. Remote Sens.*, **63**, 887–900.

Goward, S. N., and J. G. Masek, eds., 2001: Special issue: Landsat 7. *Remote Sens. Environ.*, **78**, (Issues 1–2).

Landsat 7 Data Products

To search for data, please visit the EarthExplorer or GloVis websites: earthexplorer.usgs.gov and glovis.usgs.gov

Data are no longer available through the EOSDIS Gateway (EDG). Although the method of data access has changed, there are no other changes to the processing or format of the products. Level 1 and Level 0 products that were available through the EDG can now be ordered from the USGS Earth Explorer and the Global Visualization Viewer (GloVis). As before, data processing is done by the Level 1 Product Generation System (LPGS) and National Land Archive Production System (NLAPS). Landsat 5 data cost $425 per scene (for Level 1G processing). Landsat 7 data acquired prior to the SLC malfunction cost $600 per scene (for Level 1G processing). The U.S. Geological Survey (USGS) has reduced the price of Landsat 7 scenes with gaps in data resulting from the SLC failure. Scenes that contain gaps in data have been reduced from $600 to $250. Phase I products, i.e., scenes with the gaps filled using data acquired prior to the anomaly, are also offered at a reduced price of $275 as of May 10, 2004. This product has the gap areas filled in with Landsat 7 data acquired prior to the SLC failure at a similar time of the year. Phase II products, i.e., scenes with the gaps filled using multiple SLC-off images, were made available by the end of 2004 for $300.

Product Name or Grouping	Processing Level	Coverage	Spatial/Temporal Characteristics
ETM+ *Data Set Start Date: June 29, 1999*			
Raw Digital Numbers	0R	233 orbits, each having a 183-km swath width	30 m (bands 1–5, 7), 60 m (band 6), 15 m (band 8) resolution
Calibrated Radiances	1R	183 km × 170 km	30 m (bands 1–5, 7), 60 m (band 6), 15 m (band 8) resolution
Calibrated Radiances	1G	183 km × 170 km	30 m (bands 1–5, 7), 60 m (band 6), 15 m (band 8) resolution
Note: The above data products are described in greater detail in the EOS Data Products Handbook, Volume 2, which can be found at: eospso.gsfc.nasa.gov/eos_homepage/for_scientists/data_products/vol2.php.			

Landsat 7 Data Products

LDCM

Landsat Data Continuity Mission

LDCM URLs

ldcm.nasa.gov/
ldcm.usgs.gov/

NASA and the U.S. Geological Survey (USGS) are currently developing a plan for a follow-on mission to Landsat 7 consistent with a December 23, 2005 memorandum from the Office of Science and Technology Policy. See LDCM Mission Status for additional details.

Points of Contact

- *LDCM Project Scientist:* James Irons, NASA Goddard Space Flight Center
- *LDCM Deputy Project Scientist:* Jeff Masek, NASA Goddard Space Flight Center

Other Key Personnel

- *LDCM Program Scientist:* Garik Gutman, NASA Headquarters
- *LDCM Program Executive:* Edward Grigsby, NASA Headquarters
- *LDCM Project Manager:* William Ochs, NASA Goddard Space Flight Center

Mission Type

Earth Observing System (EOS) Systematic Measurements

Launch

- *Date and Location:* To be determined
- *Vehicle:* To be determined

Relevant Science Focus Areas

(see NASA's Earth Science Program section)

- Carbon Cycle, Ecosystems, and Biogeochemistry
- Earth Surface and Interior

Related Applications

(see Applied Sciences Program section)

- Agricultural Efficiency
- Carbon Management
- Coastal Management
- Disaster Management
- Ecological Forecasting
- Energy Management
- Homeland Security
- Invasive Species
- Public Health
- Water Management

Key LDCM Facts

Joint with USGS

LDCM Project Science Office Support

Instruments: Phil Dabney, NASA GSFC

Calibration/Validation: Brian Markham, NASA GSFC, and Jim Storey, USGS

Data Acquisition: Vacant

LDCM Science Goals

- Characterize and monitor land-cover use and change over time for global climate research, polar studies, land use and land cover change, and the impacts of natural events as well as human activities on Earth's surface.

LDCM Measurement Goals

- Maintain data continuity with the Landsat system.
- Extend the Landsat record of multi-spectral, global coverage of the land surface at a moderate resolution on a seasonal basis.

LDCM Mission Background

LDCM is a joint interagency mission with the U.S. Geological Survey (USGS) to extend the Landsat record of multispectral, moderate-resolution, seasonal, global coverage of the Earth's land surface.

The Land Remote Sensing Act of 1992 directs NASA and USGS to assess various system-development and management options for a satellite system to succeed Landsat 7.

See Landsat 7 Mission description for historical details of the Landsat program.

LDCM Mission Status as of Winter/Spring 2006

(See LDCM websites for current information.)

On December 23, 2005, the Office of Science and Technology Policy (OSTP) issued a memorandum signed by Dr. John Marburger, III, adjusting the Landsat Data Continuity Mission strategy. NASA was instructed to acquire a single free-flyer spacecraft for this mission. The instrument will collect land surface data similar to that of its Landsat predecessors. The data will be delivered to the USGS, who will be responsible for mission operations as well as data collection, archiving, processing and distribution.

Efforts to implement an LDCM have been ongoing since the launch of Landsat 7 in 1999. Early plans called for NASA to purchase data meeting LDCM specifications from a privately owned and commercially operated satellite system. However, after an evaluation of proposals received from private industry, NASA cancelled the Request-for-Proposals (RFP) in September 2003.

In light of the RFP cancellation, an interagency working group was formed by the Executive Office of the President (EOP) to discuss new plans for Landsat data continuity. These discussions led to an August 13, 2004 OSTP memorandum that directed federal agencies to place Landsat-type sensors on National Polar-orbiting Operational Environmental Satellite System (NPOESS) platforms.

Following an evaluation of the technical complexity of integrating Landsat-type sensors on the NPOESS platforms, the December 2005 memorandum redirected the Departments of Commerce, Defense, the Interior, and NASA to: "proceed with the NPOESS program without incorporating a Landsat-type instrument."

The LDCM mandated by the December 2005 OSTP memorandum will collect and archive data consistent with data from the previous Landsat satellites. Expeditious progress towards the acquisition, launch, and operation of the LDCM spacecraft is anticipated, to minimize any possibility of a gap in Landsat data. Landsat 5 and Landsat 7 are still operational, but Landsat 5 is 22 years old and no redundancy remains for most of its mission critical subsystems. Landsat 7, which was launched in 1999, has lost the use of its Scan Line Corrector instrument and has lost gyro redundancy.

The U.S. Government ultimately endeavors to ensure long-term continuity of Landsat-like data. As stated in the December 2005 memorandum: "it remains the goal of the U.S. Government to transition the Landsat program from a series of independently planned missions to a sustained operational program funded and managed by a U.S. Government operational agency or agencies, international consortium, and/or commercial partnership. Concurrent with the actions cited [in the December 23, 2005 OSTP memorandum], the National Science and Technology Council, in coordination with NASA, DOI/USGS, and other agencies and EOP offices as appropriate, will lead an effort to develop a long-term plan to achieve technical, financial, and managerial stability for operational land imaging in accord with the goals and objectives of the U.S. Integrated Earth Observation System."

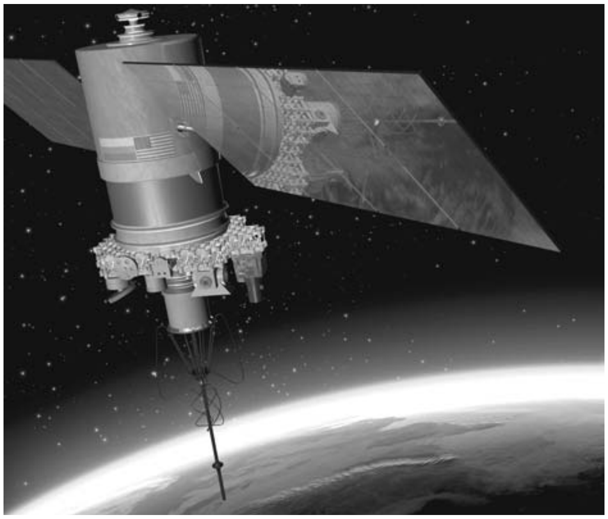
LDCM References

Irons, J. R., and W. R. Ochs, 2004: Status of the Landsat Data Continuity Mission. *2004 IEEE Int. Geosci. Remote Sens. Symp.*, Anchorage, AK, II, 1183–1185.

Irons, J. R., N. J. Speciale, J. D. McCuistion, J. G. Masek, B. L. Markham, J. C. Storey, D. E. Lencioni, and R. E. Ryan, 2003: Data specifications for the Landsat Data Continuity Mission. *2003 IEEE Int. Geosci. Remote Sens. Symp.*, Toulouse, France, II, 1335–1337.

McCuistion, J. D., C. D. Wende, and J. R. Irons, 2003: Landsat Data Continuity Mission: Creating a unique government-industry partnership for global research. *2003 IEEE Int. Geosci. Remote Sens. Symp.*, Toulouse, France, III, 1891–1893.

Meteor-3M



Meteor-3M URL
www-sage3.larc.nasa.gov/

Key Meteor-3M Facts

Spacecraft: Russian Meteor-3M

Orbit
Type: Sun-synchronous
Equatorial Crossing: 9:30 a.m.
Altitude: 1020 km ± 20 km
Inclination: 99.64°
Period: 105.3 minutes
Repeat Cycle: N/A

Dimensions: 7 m × 2 m × 2 m

Mass: 2,500 kg

Power: 600 W

Design Life: 5 years

Partners: RASA

Summary

The Stratospheric Aerosol and Gas Experiment (SAGE III) is the EOS component of the Russian Meteor-3M mission. SAGE III provides accurate, long-term measurements of ozone, aerosols, water vapor, and other key parameters of Earth's atmosphere.

Instruments

- SAGE III

Note: SAGE III is actually one of nine instruments on the Meteor-3M mission. However, the other instruments are not NASA instruments, and thus, are not described in this handbook.

Points of Contact

- *SAGE III Principal Investigator:* M. Patrick McCormick, Hampton University
- *SAGE III Project Scientist:* William Chu, NASA Langley Research Center
- *SAGE III Deputy Project Scientist:* Chip Trepte, NASA Langley Research Center

Other Key Personnel

- *SAGE III Program Scientist:* Phil DeCola, NASA Headquarters
- *SAGE III Program Executive:* Lou Schuster, NASA Headquarters
- *SAGE III Mission Manager:* Mike Cisewski, NASA Langley Research Center
- *SAGE III Program Manager:* Shahid Habib, NASA Goddard Space Flight Center

Mission Type

Earth Observing System (EOS) Systematic Measurements

Launch

- *Date and Location:* December 10, 2001, from Baikonur Cosmodrome, Russia

Relevant Science Focus Areas

(see NASA's Earth Science Program section)

- Atmospheric Composition
- Climate Variability and Change

Related Applications

(see Applied Sciences Program section)

- Air Quality
- Disaster Management

SAGE III Science Goals

- Provide global, long-term measurements of key components of Earth's atmosphere.
- Provide measurements of temperature in the stratosphere and mesosphere and profiles of trace gases, such as water vapor and nitrogen dioxide, that play significant roles in atmospheric radiative and chemical processes.

Meteor-3M Mission Background

Since the 1950s, it has become increasingly clear that human activities are modifying the composition of the atmosphere on a global scale. As the result of industrialization, the concentration of carbon dioxide has increased by about 20% since 1950. More recently, the stratospheric concentrations of chemically active gases containing chlorine, bromine, and fluorine have dramatically increased. These trends have created issues of global interest including global warming and declining levels of ozone (both globally and in the ozone 'hole' in the Antarctic). It has become evident, however, that these processes do not occur independently of one another and can only be understood in the context of a global system. Accurate and precise measurements are needed to unravel complex and interactive relationships between chemical, radiative, and dynamical processes in the atmosphere, ocean, and on land.

The Russian Aviation and Space Agency (RASA) assembled a mission to measure temperature and humidity profiles, clouds, surface properties, and high-energy particles in the upper atmosphere. The Meteor-3M spacecraft is an advanced model of the Meteor spacecraft that was developed over 30 years ago. Included among the instruments on Meteor-3M is the Third Stratospheric Aerosol and Gas Experiment (SAGE III). The Meteor-3M mission, along with the SAGE III mission, was terminated on March 6, 2006, because of a power supply system failure resulting in loss of communication with the satellite.

SAGE III

Stratospheric Aerosol and Gas Experiment

The SAGE III instrument provides long-term measurements of key components of Earth's atmosphere that are important in helping scientists understand how natural processes and human activities influence our climate. The most important of these are the vertical distribution of aerosols and ozone from the upper troposphere through the stratosphere. In addition, SAGE III also provides unique measurements of temperature in the stratosphere and mesosphere and profiles of trace gases such as water vapor and nitrogen dioxide that play significant roles in atmospheric radiative and chemical processes. SAGE III makes long-term measurements of these key components and provides the congruent aerosol and gaseous data important to radiative and atmospheric chemistry studies.

Key SAGE III Facts

Heritage: SAM II, SAGE I, SAGE II

Instrument Type: Grating spectrometer

Scan Type: Solar and lunar occultation

Calibration: Self-calibrating solar and lunar occultation, with measurements within nine spectral regions between (290-1,550 nm), to study aerosols, O_3, OClO, NO_2, NO_3, H_2O, temperature, and pressure

Swath: N/A (looks at the Sun and/or moon through Earth's limb)

Spatial Resolution: 1–2 km vertical

Dimensions: 73 cm × 45 cm × 93 cm

Mass: 76 kg

Duty Cycle: During solar and lunar Earth occultation

Power: 80 W (average)

Data Rate: 115 kbps

Thermal Control: Passive, heaters, and thermal-electric cooler

Thermal Operating Range: 10–30° C

FOV: ±185° azimuth, 13–31° elevation, dependent on orbital altitude

Instrument IFOV: < 0.5 km vertical at 20-km tangent height

Pointing requirements (platform+instrument, 3σ):
Control: 1°
Knowledge: 0.25°/axis
Stability: 30 arcsec/s per axis

Responsible Center: NASA LaRC

Partner: Ball Aerospace

SAGE III is a grating spectrometer that measures ultraviolet/visible energy. It relies upon the flight-proven designs used in the Stratospheric Aerosol Measurement (SAM I) and SAGE I and II instruments. The new SAGE III design incorporates charge coupled device (CCD)-array detectors and a 16-bit A/D converter. The additional wavelengths and the ability to operate during both lunar and solar occultation have several benefits, as they: improve aerosol characterization and gaseous retrievals of O_3, H_2O, and NO_2; add retrievals of temperature, pressure, NO_3 and OClO; extend the vertical range of measurements; provide a self-calibrating instrument independent of any external data; and expand the sampling coverage. The global scientific community uses the information obtained from SAGE III to help improve their understanding of Earth's climate, of climate change, and human-induced ozone trends.

The science objectives of SAGE III are to:

- Retrieve global profiles (with 1-to-2-km vertical resolution) of atmospheric aerosols, O_3, H_2O, NO_2, NO_3, OClO, temperature, and pressure in the mesosphere, stratosphere, and troposphere.
- Investigate the spatial and temporal variability of the measured species in order to determine their role in climatological processes, biogeochemical cycles, the hydrologic cycle, and atmospheric chemistry.
- Characterize tropospheric and stratospheric aerosols and upper tropospheric and stratospheric clouds, and investigate their effects on Earth's environment, including radiative, microphysical, and chemical interactions.
- Extend the SAM II, SAGE I, and SAGE II self-calibrating solar-occultation data sets (begun in 1978), enabling the detection of long-term trends.
- Provide atmospheric data essential for the calibration and interpretation/correction of other satellite sensors, including EOS and ground-based sensors.

As indicated above, SAGE III takes advantage of both solar and lunar occultations to measure aerosol and gaseous constituents of the atmosphere. Most of the objectives rely on the solar-occultation technique, which involves measuring the effects of extinction of solar energy by aerosol and gaseous constituents in the spectral region 0.29–1.55 µm during spacecraft sunrise and sunset events. For example, during a sunset event, exoatmospheric solar-limb data are obtained when the Sun-satellite vector is high above the Earth's atmosphere. As the Sun sets, a series of scans through the atmosphere is performed during which measurements of the solar transmission through the atmosphere are made. Because all atmospheric measurements are ratioed to the exoatmospheric solar-limb profiles taken during the same event, the instrument is nearly self-calibrating, and the retrieved data are not susceptible to long-term instrument degradation.

The moon is used as another source of light for occultation measurements. In the spectral region 0.4–0.95 µm, the moon has a relatively flat, i.e., grey, albedo. By taking a ratio of an appropriate set of exoatmospheric scans of the moon to an appropriate set of exoatmospheric scans of the Sun, the structure in the solar spectrum is retrieved and the average lunar spectral albedo is obtained. This average lunar spectral albedo can be used along with the extinction cross sections of all absorbing species to determine an optimal fit to the measurements.

Meteor-3M References

Chu, W. P., and L. E. Mauldin III, 1999: Overview of SAGE III experiment, in A. M. Larar, ed., *Proc. SPIE 3756, Optical and Spectroscopic Techniques and Instrumentation for Atmospheric and Space Research III*, 102–109.

Chu, W. P., C. R. Trepte, J. M. Zawodny, L. W. Thomason, M. S. Cisewski, D. Rault, G. Taha, R. Moore, and D. Risley, 2003: First year measurements of Stratospheric Aerosol and Gas Experiment III/Meteor, in A. M. Larar, J. A. Shaw, and Z. Sun, eds., *Proc. SPIE 5157, Optical Spectroscopic techniques and Instrumentation for Atmospheric and Space Research V*, 42–46.

McCormick, M. P., 1991: SAGE III capabilities and global change. Paper 91-0051, 29th Aerospace Sciences Meeting, 7-10 January 1991, Reno, Nevada, American Institute of Aeronautics and Astronautics, Washington, DC.

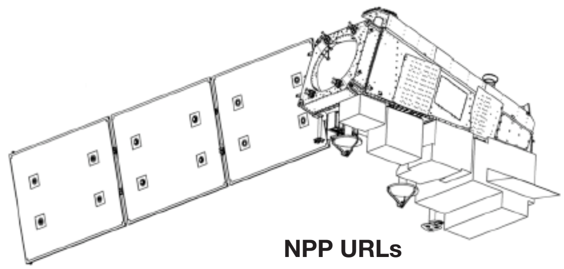
Meteor-3M Data Products

Product Name or Grouping	Processing Level	Coverage	Spatial/Temporal Characteristics
SAGE III *Data Set Start Date: February 27, 2002, Data Set End Date: March 6, 2006*			
Level 1B Transmission (≥ 80 wavelengths) Solar Events	1B	Global, for altitudes of 0–100 km	1.5 km horizontal resolution (hres) (Solar), 0.5 km vertical resolution (vres)/ 28 solar events daily
Aerosol Extinction Stratospheric Optical Depth (at 8 wavelengths) Aerosol to molecular extinction at 1020 nm (Solar only)	2	Global, 0–30 km	1.5 km hres (Solar), 0.5 km vres/ 28 solar events daily
Cloud Presence	2	Global, 6–30 km	1.5 km hres (Solar), 0.5 km vres/ 28 solar events daily
H_2O Concentration	2	Global, 0–50 km	1.5 km hres (Solar), 0.5 km vres/ 28 solar events daily
NO_2 Concentration	2	Global, 10–50 km	1.5 km hres (Solar), 3.5 km hres (Lunar), 0.5 km vres/28 solar events daily
NO_2 Slant Path Column Amount	2	Global, 10–50 km	1.5 km hres (Solar), 3.5 km hres (Lunar), 0.5 km vres/28 solar events daily
NO_3 Concentration (Lunar Only)	2	Global, 20–55 km	3.5 km hres (Lunar), 0.5 km vres
O_3 Concentration	2	Global, 6–85 km	1.5 km hres (Solar), 3.5 km hres (Lunar), 0.5 km vres/28 solar events daily
O_3 Slant Path Column Amount	2	Global, 50–85 km	1.5 km hres (Solar), 3.5 km hres (Lunar), 0.5 km vres/30 solar events daily
OClO Concentration	2	Global, 15–25 km	3.5 km hres (Lunar), 0.5 km vres
Pressure	2	Global, 0–85 km	1.5 km hres (Solar), 3.5 km hres (Lunar), 0.5 km vres
Temperature Profile (Solar only)	2	Global, 0–85 km	1.5 km hres, 0.5 km vres

Meteor-3M Data Products

NPP

National Polar-orbiting Operational Environmental Satellite System (NPOESS) Preparatory Project



NPP URLs

jointmission.gsfc.nasa.gov
www.ipo.noaa.gov

Summary

NPP is a joint mission with the NPOESS Integrated Program Office (IPO). Its two main objectives are to provide NASA and the broader Earth science community with continuation of calibrated, validated, and geo-located global imaging and sounding products beyond the Earth Observing System (EOS) missions and to provide risk reduction for NPOESS through pseudo-operational demonstration and validation of instruments and algorithms prior to the first NPOESS flight. In this manner, NPP bridges the EOS missions to the NPOESS missions, supporting the transition of selected long-term systematic Earth-science measurements from EOS to operational systems. The launch is planned for 2008 with a mission duration of 5 years.

Instruments

- Advanced Technology Microwave Sounder (ATMS)
- Cross-track Infrared Sounder (CrIS)
- Ozone Mapping and Profiler Suite (OMPS)
- Visible Infrared Imaging Radiometer Suite (VIIRS)

Points of Contact

- *NPP Project Scientist:* James Gleason, NASA Goddard Space Flight Center
- *NPP Deputy Project Scientist:* Jeffrey Privette, NASA Goddard Space Flight Center
- *NPP Deputy Project Scientist for Calibration and Validation:* James Butler, NASA Goddard Space Flight Center

Key NPP Facts

Joint mission with the tri-agency Integrated Program Office [Department of Commerce (DoC), Department of Defense (DoD), and NASA]

International partners include the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) and the Japan Aerospace Exploration Agency (JAXA).

Orbit

Type: Sun-synchronous
Equatorial Crossing: 10:30 a.m.
Altitude: 824 km
Inclination: 97.1°
Period: 101 minutes
Repeat Cycle: 16 Day (8-day quasi-repeat)

Dimensions: 4.028 m × 2.610 m × 2.206 m

Mass: 2001 kg

Power: 2017 W

Downlink: Svalbard Ground Station once per orbit; backup telemetry and command via TDRSS

Design Life: 5 years

Direct Broadcast: Mission data on X-band; telemetry and command on S-Band

NPP Partners

Spacecraft: Ball Aerospace & Technologies Corp.
ATMS: Northrop Grumman Electronic Systems
CrIS: ITT Industries, Inc.
OMPS: Ball Aerospace, Inc.
VIIRS: Raytheon Santa Barbara Remote Sensing
Data Processing: NPOESS IDPS production facility at NOAA/NESDIS
Ground Operations: NPOESS IPO
Validation: Northrop Grumman Space Technology, IPO and NASA

NPP Organization

NPP's management is a joint venture between NASA and the IPO.

Other Key Personnel

- *NPP Program Scientist:* Diane Wickland, NASA Headquarters
- *NPP Program Executive:* Andrew Carson, NASA Headquarters

Mission Type

Next Generation Systematic Measurement

Launch

- *Date and Location:* No earlier than 2008, from Vandenberg Air Force Base, California

Relevant Science Focus Areas

(see NASA's Earth Science Program section)

- Atmospheric Composition
- Climate Variability and Change
- Carbon Cycle, Ecosystems, and Biogeochemistry
- Water and Energy Cycles
- Weather

Related Applications

(see Applied Sciences Program section)

- Agricultural Efficiency
- Air Quality
- Aviation
- Carbon Management
- Coastal Management
- Disaster Management
- Ecological Forecasting
- Homeland Security
- Invasive Species
- Public Health
- Water Management

NPP Science Goals

NPP will provide NASA with continuation of a set of global-change observations initiated by the EOS Terra, Aqua, and Aura missions. The observations will contribute to the Systematic Measurements element of NASA's ESE Research Strategy for 2000–2010. The systematic measurements will be used in the development of consistent, long-term data records from multi-instrument, multi-platform and multi-year observations, with due attention to calibration and validation. In that context, NPP's Environmental Data Records (EDRs), similar to EOS Level 2 swath products, will be generated in near-real time in NPOESS production facilities. NASA will help validate and enhance the algorithms, driving them toward science-grade quality where possible. NPP also serves as a risk-reduction demonstration for key aspects of NPOESS, the nation's future polar-orbiting operational satellite system. Together, NPP's objectives will allow NASA science programs to transition their systematic observation requirements from research grade missions to NPOESS and other operational missions.

NPP Instruments

ATMS

Advanced Technology Microwave Sounder

A 22-channel passive microwave radiometer with a swath width of 2300 km. Its heritage is the AMSU-A (A1/A2) and the AMSU-B (HSB and MHS). It provides the initial estimate of temperature and moisture profiles for input to an infrared algorithm as well as an all-weather set of profiles.

CrIS

Cross-track Infrared Sounder

A Michelson interferometer with a swath width of 2200 km and 1297 spectral channels. Its heritage is the High Resolution Infrared Radiation Sounder (HIRS), the Atmospheric Infrared Sounder (AIRS), and the Infrared Atmospheric Sounding Interferometer (IASI). It will produce daily global sets of high-resolution temperature and moisture profiles for scenes with < 50% cloud cover. It is co-registered with the ATMS and is designed to work in conjunction with it.

OMPS

Ozone Mapping and Profiler Suite

Comprises two sensors—a nadir sensor and a limb sensor, with the latter composed of three separate instruments. The suite measures solar-scattered radiation to map the vertical and horizontal distribution of ozone in Earth's atmosphere.

The nadir total-column UV spectrometer measures the scene radiance at 300–380 nm with a resolution of 1 nm sampled at 0.42 nm and a 23-hour ground revisit time with a resolution better than 50 km × 50 km. The nadir profile spectrometer measures at 250–320 nm with the same spectral sampling, in a single ground pixel of 250 km ×
250 km. The UV/VIS limb sensor measures the along-track limb scattered solar radiance with 1-km vertical sampling in the spectral range 290–1000 nm.

NPP Mission Background

NPP has been formulated using an end-to-end mission-life-cycle methodology. The NPP payload includes four instruments: VIIRS, CrIS, ATMS, and OMPS. IPO will provide VIIRS, CrIS and OMPS, and NASA will provide ATMS. VIIRS will provide daily global imagery through a multispectral scanning radiometer. CrIS will adopt Michelson interferometer technology to provide high-spectral-resolution sounding of the Earth and atmosphere. Using advanced microwave-receiver electronics technologies, ATMS will combine the passive microwave observation capabilities of three heritage instruments (Advanced Microwave Sounding Unit (AMSU) A1/A2 and Microwave Humidity Sounder (MHS)) into a single small instrument. CrIS and ATMS are complementary, and together comprise the Cross-track Infrared Microwave Sounding Suite (CrIMS) sounding package. OMPS will continue the Total Ozone Mapping Spectrometer (TOMS)/ Solar Backscatter Ultraviolet (SBUV) heritage of ozone sounding and also provide new limb-profiling products. All sensors are new designs.

The spacecraft for NPP will directly transmit stored mission sensor data to a receiving station in Svalbard, Norway, and will also provide continuous direct broadcast of real-time sensor data. The mission data will be routed on communications networks from Svalbard to the continental United States. The NPOESS Interface Data Processing Segment (IDPS) will provide pseudo-operational processing of the mission data into Environmental Data Records (EDRs) for use by the operational community. NASA will assess sensor and algorithm performance through its Science Data Segment (SDS) and will attempt to improve the IDPS in cases where it is deemed insufficient to meet NASA's research goals. SDS will also support NASA-funded processing centers that use NPP data in the development of multimission long-term climate-quality data records. All products will be archived in NOAA's Comprehensive Large Array data Stewardship System (CLASS).

Spacecraft flight operations and the spacecraft operations control center will control the spacecraft and instruments, including on-orbit instrument-calibration activities. IPO will provide the communication, command, control, and IDPS systems, and NASA will provide the spacecraft. NASA will also provide state-of-the-art hardware, algorithms, and system technology to the operational program.

The NPP Project completed its Mission Confirmation Review in October 2003.

Project Science Group (PSG)

The PSG consists of government, university, and contractor staff located at or near NASA GSFC. Under the leadership of the Project Scientists, the group is responsible for coordinating NASA's NPP science activities, providing sensor calibration and characterization advice and augmentation to mission and sensor contractors, facilitating NASA NPP Science Team efforts to assess and enhance the industry-supplied algorithms, guiding the design and managing the Science Data Segment, and communicating Science Team suggestions for algorithm improvements to the IPO and mission

NPP Instruments *(cont.)*

VIIRS

Visible Infrared Imaging Radiometer Suite

A 22-band, multi-spectral scanning radiometer with a 3040-km swath width. Some bands have dual gains. It derives its heritage from the Advanced Very High Resolution Radiometer (AVHRR), Operational Linescan System (OLS), MODIS, and Sea-viewing Wide Field-of-view Sensor (SeaWiFS). There are both imagery and moderate-resolution bands with effective pixel sizes of 370 m and 740 m at nadir, respectively. Pixel-size variation across the swath is constrained.

prime contractor. PSG will also ensure that the SDS enables the production of long-term multi-mission climate data records in the future.

Science Team

The 24-member NASA NPP Science Team was competitively selected in September of 2003 to assess the usefulness of NPP's industry-supplied operational products for NASA's global change research program. In addition to reviewing algorithm theory and evaluating the pre-launch production codes, the team will analyze and suggest improvements to sensor calibration, product validation, and the IDPS and SDS components. Ultimately, the team seeks to develop approaches for the IDPS operational products to meet NASA's science requirements. The NPP Team will help lead the transition from NASA's traditional mission-oriented science teams, e.g., MODIS, to theme-based measurement-oriented science teams, e.g., land biophysical products, which bridge multiple missions and sensors.

ATMS

Advanced Technology Microwave Sounder

Provides high-spatial-resolution microwave data to support temperature- and humidity-sounding generation in cloud-covered conditions.

ATMS Background

ATMS extends the measurement series initiated by its heritage sensors AMSU-A, and AMSU-B (Humidity Sounder for Brazil (HSB) and MHS). It is already flying or planned to fly on NOAA-15, -16, -17, -18, and -19; METOP; and Aqua. ATMS has three more channels than AMSU, better sampling, and a sharper spatial resolution.

ATMS Science

ATMS is a total-power radiometer with cross-track scanning. Working in unison with CrIS, ATMS forms the sensor package called the Cross-track Infrared Microwave Sounding Suite (CrIMSS). This suite provides daily global observations of temperature and moisture profiles at high spatial resolution.

ATMS' temperature-sounding channels have 2.2° beams and are Nyquist-sampled in both the cross-track and the down-track directions. ATMS uses a stable onboard through-the-antenna calibration. For each complete scan cycle (8 scans/3 s), the detectors view 2 distinct calibration targets to keep the instrument calibration highly stable.

The data compiled by CrIMSS will be used to create global models of temperature and moisture profiles. This information will provide a much wider range of information on Earth's weather systems and allow for greater forecasting abilities than was previously possible. CrIMMS will provide soundings of the entire planet

Key ATMS Facts

Works in unison with CrIS

Heritage: AMSU-A and AMSU-B (HSB and MHS)

Heritage Missions: NOAA-15, -16, -17, Meteorological Operational Satellite (METOP), and Aqua

Instrument Type: Total Power Radiometer

Scan Type: Cross-track

Incidence Viewing: 2300 km

Calibration: On-board, two-point calibration

Field of View (FOV): Ch 1–2: 5.2°; Ch 3–16: 2.2°; Ch 17–22: 1.1°

Instrument IFOV: Ch 1–2: 75 km; Ch 3–16: 33 km; Ch 17–22: 15 km at nadir

Swath: 2300 km

Spatial Resolution: See IFOV

Spectral Range: 22 channels (23–183 GHz)

Dimensions: 70 cm (vel.) × 60 cm (nadir) × 40 cm

Mass: 85 kg

Power: 110 W

Data Rate: 30 Kbps

Direct Broadcast: Yes

at better than 1 K/500-m accuracy. It is hoped that the suite will greatly increase weather forecasting range and accuracy broadly across the globe.

CrIS

Cross-track Infrared Sounder

CrIS Background

CrIS is a Michelson interferometer infrared sounder designed to measure scene radiance and calculate the vertical distribution of temperature, moisture, and pressure in Earth's atmosphere. CrIS was designed to work in unison with the ATMS, together creating the CrIMSS. The objective of CrIMSS is to provide global three-dimensional soundings of atmospheric temperature and moisture as well as provide data on other geophysical parameters.

The technology implemented within NPP provides risk reduction for the NPOESS project. The High Resolution Infrared Radiation Sounder (HIRS), a heritage sensor of CrIS, has provided early soundings of Earth's atmosphere. The NPOESS Airborne Sounder Testbed (NAST) has conducted successful airplane simulations for both ATMS and CrIS, providing both flight validation and a preview of high-resolution spectral and spatial products. The CrIS is the follow-on sounder to the EOS Atmospheric Infrared Sounder (AIRS), which has proven results on its current operation on Aqua. The CrIS effort consists of a space-based sensor that produces Raw Data Records (RDRs) and ground-based science algorithms that produce calibrated Sensor Data Records (SDRs) and Environmental Data Records (EDRs). The CrIS sensor forms a key component of the larger CrIMSS and is intended to operate within the context of the CrIMSS architecture. CrIS EDR algorithms generate EDR products for the entire CrIMSS suite.

CrIS Science

CrIS will take high-spectral-resolution measurements of Earth's radiation to determine the vertical distribution of temperature, moisture, and pressure in the atmosphere. CrIS uses a Michelson interferometer infrared sounder covering the spectral range of approximately 3.9–14.4 μm (655–2550/cm). It is the primary instrument for satisfying three Environmental Data Records (EDRs), for atmospheric temperature, moisture, and pressure.

CrIS will provide over 1000 spectral channels of information in the infrared region at a high horizontal spatial resolution and will be able to measure temperature profiles with improved vertical resolution to an accuracy approaching 1 K. This improved accuracy is necessary for increasingly sophisticated forecast models. It will help both short-term weather 'nowcasting' and long-term forecasting. Its infrared sensors will provide high-resolution data that will also assist in understanding El Niño and other major climate phenomena.

Key CrIS Facts

Heritage: HIRS, AIRS, IASI

Instrument Type: Michelson interferometer infrared sounder

Scan Type: Step-scanning

Incidence Viewing: ± 48.33°

FOV:
- # of FOV: 3 × 3
- FOV Diameter (round): 14 km
- FOV Shape Match: < 0.05%

Instrument FOV: 14 km

Swath: 2200 km

Spatial Resolution:
- LWIR: 655–1095/cm
- MWIR: < 1.25/cm
- SWIR: < 2.50/cm

Spectral Range:
- LWIR Band: 655–1095/cm
- MWIR Band: 1210–1750/cm
- SWIR Band: 2155–2550/cm

Dimensions: 87.8 cm × 93.8 cm × 73.1 cm

Mass: 148 kg

Power: 118 W

Data Rate: 1.48 Mbps

Direct Broadcast: Yes

OMPS

Ozone Mapping and Profiler Suite

OMPS Background

The NASA Solar Backscatter Ultraviolet (SBUV) and Total Ozone Mapping Spectrometer (TOMS) series of instruments began operation with the Nimbus-7 TOMS and the NOAA SBUV/2 series of instruments. They have been conducting measurements of atmospheric ozone since 1978 and 1984, respectively. The Earth Probe TOMS instrument has been used to continue the record of ozone measurements, and as of July 15, 2004, it was joined by the Ozone Monitoring Instrument on the Aura spacecraft. The observations provided by these two systems will be extended and augmented by the next generation of U.S. ozone-monitoring instruments, OMPS. OMPS will first fly on the NPP mission to demonstrate its performance and to further insure continuity and will then become operational on NPOESS.

The suite consists of three advanced hyperspectral-imaging spectrometers where each has its own thermoelectric CCD-array detectors. Two nadir instruments provide a continuation of TOMS and SBUV/2 total-column and ozone-profile measurements but with improved accuracy and precision using advanced algorithms in order to meet the EDR requirements. The Limb Profiler provides ozone profiles with 3-km resolution, which is improved over the SBUV/2 vertical resolution. The instrument views solar- scattered light in the ultraviolet and the visible. The instrument and algorithm have heritage from the Shuttle Ozone Limb Sounding Experiment/ Limb Ozone Retrieval Experiment (SOLSE/LORE) instruments flown on the Space Shuttle and Canadian and European instruments on free-flying satellites. OMPS is one of two NPP/NPOESS instruments that have long-term stability requirements to meet trend-monitoring requirements.

OMPS Science

The OMPS Nadir Mapper system will provide total-column-ozone estimates with full coverage of the sunlit Earth once per day. These will be augmented by total-column-ozone estimates from the NPP/NPOESS Cross-track Infrared Sounder (CrIS) measurements, which will be available for both day and night orbital views, including polar night.

The Nadir Mapper and Nadir and Limb Profiler records will extend the 25-year total-ozone and ozone-profile records used by ozone-assessment researchers and policy makers to track the health of the ozone layer. OMPS will monitor the Antarctic ozone hole and will also monitor the high-latitudes of the Northern Hemisphere during winter and spring, when the largest ozone trends are typically observed. The improved vertical resolution of the Limb Profiler estimates will allow better testing and monitoring of the complex chemistry involved in ozone destruction near the tropopause. Research algorithms will produce tropospheric aerosol characteristics and tropospheric ozone characteristics.

These ozone products will be assimilated into forecast models, where they will be combined with cloud predictions to produce

Key OMPS Facts

Heritage: TOMS, SBUV

Instrument Type: Three hyperspectral imaging spectrometers, two grating and one prism, named the Nadir Mapper, Nadir Profiler, and Limb Profiler, respectively. Each instrument has a thermoelectrically cooled charge-coupled device (CCD) array detector

Scan Type: The nadir instruments are pushbroom, and the limb instrument images the Earth limb on the detector

Calibration: Extensive prelaunch calibration. Onboard calibration includes light-emitting diode (LED) for CCD flat fielding, working, and reference solar diffusers. Wavelength calibration is achieved by observing solar Fraunhofer lines.

Instrument FOV:

Nadir Mapper: 110 × 0.3°

Nadir Profiler: 16.7 × 0.3°

Limb Profiler: 1.95° (3 sets separated by 4.3°)

Spatial Resolution:

Nadir Mapper: 50 km × 50 km with 2600 km swath

Nadir Profiler: 250 km × 250 km horizontal, 8 km vertical over 0–60 km altitude range

Limb Profiler: 3-km vertical over 0–60 km altitude range with retrievals from the tropopause to 60 km; three sets separated by 500 km

Spectral Range:

Nadir Mapper: 300–380 nm

Nadir Profiler: 250–310 nm

Limb Profiler: 290–1000 nm

Spectral Sampling Interval (FWHM: full width half maximum):

Nadir Mapper: 2.4 pixels per FWHM

Nadir Profiler: 2.4 pixels per FWHM

Limb Profiler: 2.0 pixels per FWHM

Spectral Resolution (FWHM):

Nadir Mapper: 1.0 nm

Nadir Profiler: 1.0 nm

Limb Profiler: 1.5–40 nm

Revisit Time:

Nadir Mapper: 24 hours

Limb Profiler: 4 days (average)

Dimensions: 35 cm × 54 cm × 56 cm

Mass: 69 kg

Power: 108 W

Duty Cycle: Daytime only

Data Rate: 188 Kbps

Ultraviolet Index forecasts. The Nadir Profiler and Limb Profiler will provide estimates of the vertical ozone profile for the suborbital track on the sunlit portions of each orbit. The ozone column and profile estimates will be assimilated into numerical weather models to improve the fidelity of atmospheric heating calculations and into atmospheric chemistry models to improve air quality monitoring.

VIIRS

Visible Infrared Imaging Radiometer Suite

VIIRS Background

VIIRS extends the measurement series initiated by its heritage sensors, the polar-orbiting Advanced Very High Resolution Radiometer (AVHRR) and MODIS. VIIRS may be considered an evolved form of the MODIS, with similar performance, spatial resolution, and spectral sampling. Although VIIRS has just 22 bands compared to 36 for MODIS, it employs dual-gain technology such that most MODIS measurements are continued. VIIRS has a nadir pixel resolution comparable to MODIS, but VIIRS has constrained pixel growth with scan angle such that it has superior resolution at the edge of scan. The constrained growth is achieved through onboard detector aggregation as the telescope moves from the swath edge to nadir. Like MODIS, VIIRS has several onboard calibration systems. In contrast to MODIS, however, VIIRS uses a rotating telescope and all reflective (rather than transmissive) fore-optics. VIIRS and OMPS are the two NPP/NPOESS instruments that have long-term stability requirements to meet trend-monitoring requirements.

VIIRS Science

VIIRS will collect visible/infrared imagery and radiometric measurements of land, atmospheric, cryospheric, and oceanic parameters. These data will be used to generate 29 EDRs, which are roughly equivalent to NASA Level 2 swath products. The VIIRS EDRs cover a broad range of parameters, including cloud and aerosol properties, ocean color and sea surface temperature, ice motion and temperature, and a diverse set of land products, including active fire detection, land surface temperature, and albedo. Most products will be generated globally each day. The sensor and algorithm system was designed to meet IPO-specified requirements. These requirements are generally similar to MODIS product performance requirements. At night VIIRS operates 11 of its 22 spectral bands, and produces a reduced set of EDRs.

Key VIIRS Facts

Heritage: MODIS (onboard Terra and Aqua), AVHRR, and OLS

Instrument Type: Scanning radiometer

Calibration: Onboard blackbody radiator for thermal bands, onboard solar diffuser panel for solar reflective bands, and a space-view port

Instrument IFOV: Moderate-resolution detectors: 0.742 km along track, 0.318 along scan at nadir; Imagery-resolution detectors: 0.371 km along track, 0.095 along scan.

Number of Bands: 22

Spatial Resolution (3 imagery spatial resolutions):

- Imagery resolution bands: 375 m at nadir
- Moderate resolution bands: 750 m at nadir
- Near-constant-contrast band: 750 m across full scan

Spectral Bands:

- Wavelength Range: 0.412–12.013 µm
- Visible/Near IR: 9 plus day/night panchromatic band
- Mid-Wave IR: 8
- Long-Wave IR: 4

Imaging Optics: 20-cm aperture, 114-cm focal length

Dimensions: 133 cm × 143 cm × 85 cm

Mass: 252 kg

Power: Orbit average = 191 W

Direct Broadcast: Yes

Data-Acquisition Parameters:

- Scanned Swath: ± 55.84°, 3040 km
- Downtrack Swath: 11.8 km, 16–32 detectors in track
- Scan Period: 1.786 s
- Horizontal Sample Interval on Ground at End of Scan: Moderate bands < 1.6 km; Imagery bands < 0.80 km
- Data Quantization: 12–14 bit A/D converters for lower noise
- High-Rate Data (Rice Compression): 7.41 Mbps (Maximum: 10.5 Mbps)

NPP References

ATMS References

Galin, I, D. H. Brest, and G. R. Martin, 1993: The DMSP SSM/T-2 microwave water vapor profiler. *Proc. SPIE*, **1935**, 189–198.

Jarrett, M. L, *et al.*, 1993: Verification of AMSU-B design. *Proc. SPIE*, **1935**, 136–147.

Patel, P. K., and J. Mentall, 1993: The Advanced Microwave Sounding Unit-A (AMSU-A). *Proc. SPIE*, **1935**, 130.

Rosenkranz, P. W., 2001: Retrieval of temperature and moisture profiles from AMSU-A and AMSU-B measurements. *IEEE Trans. Geosci. Remote Sens.*, **39**, 2429–2435.

Shiue, J., 2004: Evolution of microwave radiometers for remote sensing of atmospheric temperature and humidity for satellites, from Nimbus to NPOESS and beyond. WSEAS Conference, CSCC paper 487–712.

CrIS References

CrIS Algorithm Theoretical Basis Document, ITT Doc. No. 8180004, March 2001.

Glumb R., D. Jordan, and J. Predina, 2000: The Crosstrack Infrared Sounder. SPIE 2000 Int. Sympos. Optical Sci. and Technology, San Diego, CA., Paper Number 4131-14.

Predina, J. P., and R. J. Glumb, 2000: The Crosstrack Infrared Sounder (CrIS): Data algorithms and products. The 11th International TIROS Operational Vertical Sounder (ITOVS) Conference.

Williams, K. L., K. R. Schwantes, D.C. Jordan, and R. J. Glumb, 2001: Derivation and allocation of requirements for the Crosstrack Infrared Sounder. *Proc. SPIE*, **4486**, 425–436, doi:10.1117/12.455125.

OMPS References

Bhartia, P. K., R. D. McPeters, C. L. Mateer, L. E. Flynn, and C. Wellemeyer, 1996: Algorithm for the estimation of vertical ozone profiles from the backscattered ultraviolet technique. *J. Geophys. Res.*, **101(D13)**, 18,l793–18,806.

Flittner, D. E., B. Herman, and P. K. Bhartia, 2000: The retrieval of ozone profiles from limb scatter measurements: Theory. *Geophys. Res. Lett.*, **27**, 2601–2604.

Haley, C. S., C. von Savigny, S. Brohede, C. E. Sioris, I. C. McDade, E. J. Llewellyn, and D. P. Murtagh, 2004: A comparison of methods for retrieving stratospheric ozone profiles from OSIRIS limb-scatter measurements. *Adv. Space Res.*, **34**, 769–774.

McPeters, R. D., S. Janz, E. Hilsenrath, T. Brown, D. Flittner, and D. Heath, 2000: The retrieval of ozone profiles from limb scatter measurements: Results from the Shuttle Ozone Limb Sounding Experiment. *Geophys. Res. Lett.*, **27**, 2597–2600.

McPeters, R. D., P. K. Bhartia, A. J. Krueger, J. R. Herman, B. M. Schlesinger, C. G. Wellemeyer, C. J. Seftor, G. Jaross, S. L. Taylor, T. Swissler, O. Torres, G. Labow, W. Byerly, and R. P. Cebula, 1996: Nimbus-7 Total Ozone Mapping Spectrometer (TOMS) Data Products User's Guide, NASA Reference #1384. [Available online at: ftp://toms.gsfc.nasa.gov/pub/nimbus7/NIMBUS7_USERGUIDE.PDF.]

von Savigny, C., C. S. Haley, C. E. Sioris, I. C. McDade, E. J. Llewellyn, D. Degenstein, W. F. J. Evans, R. L. Gattinger, E. Griffioen, E. Kyrölä, N. D. Lloyd, J. C. McConnell, C. A. McLinden, G. Mégie, D. P. Murtagh, B. Solheim, and K. Strong, 2003: Stratospheric O_3 profiles retrieved from limb scattered sunlight radiance spectra measured by the OSIRIS instrument on the Odin satellite. *Geophys. Res. Lett.*, **30(14)**, 1755, doi: 10,1029/2002GL016401.

VIIRS References

Murphy, R. E., W. L. Barnes, A. I. Lyapustin, J. Privette, C. Welsch, F. DeLuccia, H. Swenson, C. F. Schueler, P. E. Ardanuy, and P. S. M. Kealy, 2001: Using VIIRS to provide data continuity with MODIS. *Proc. Int. Geosci. Remote Sens. Symp. 2001*, Sydney, Australia, IEEE International, **3**, 1212–1214

Scalione, C. T., H. Swenson, F. DeLuccia, C. Schueler, E. Clement, and L. Darnton, 2003: Design evolution of the NPOESS VIIRS instrument since CDR. *Proc. Int. Geosci. Remote Sens. Symp. 2003*, Toulouse, France, IEEE International, **5**, 3039–3042.

Schueler, C., J. E. Clement, L. Darnton, F. DeLuccia, T. Scalione, and H. Swenson, 2003: VIIRS sensor performance. *Proc. Int. Geosci. Remote Sens. Symp. 2003*, Toulouse, France, IEEE International, **1**, 369–372.

Schueler, C. F., J. E. Clement, S. W. Miller, P. M. Kealy, P. E. Ardanuy, S. A. Cota, F. J. De Luccia, J. M. Haas, S. A. Mango, K. S. Speidel, and H. Swenson, 2003: NPOESS VIIRS: Next-generation polar-orbiting atmospheric imager. *Proc. SPIE Int. Soc. Opt. Eng.*, **4891**, 50.

Additional NPP Documents

The IPO NPOESS Archive is a collection of documents both current and historical. Some date to the beginnings of NPOESS and IPO. The initial contents for this collection were obtained from the original NPOESS online library (npoesslib.ipo.noaa.gov) in July 2003.

IPO NPOESS Library URL:

npoesslib.ipo.noaa.gov/

NPP Data Products

NPP will provide Raw Data Records (RDRs) (roughly equivalent to NASA's Level 0 data definition), Sensor Data Records (SDRs) (NASA's Level 1b), and Environmental Data Records (EDRs) (NASA's Level 2). All RDRs and SDRs, and nearly all EDRs, will be provided in swath (granule)-format only. The data will be packaged in Hierarchical Data Format 5 (HDF5) with limited Quality Assurance bits and metadata.

Product Name	Spatial Resolution
CrIMSS	
Atmospheric Vertical Moisture Profile*	3 km at nadir
Atmospheric Vertical Temperature Profile*	3 km at nadir
Pressure Vertical Profile	3 km at nadir
Clear Column Radiances	3 km at nadir
OMPS	
Ozone Total Column/Profile	50 km at nadir
VIIRS	
Imagery*	0.4 km at nadir
Precipitable Water	0.75 km at nadir
Suspended Matter	1.6 km at nadir
Aerosol Optical Thickness	1.6 km (over ocean), 9.6 km (over land) at nadir
Aerosol Particle Size	1.6 km (over ocean), 9.6 km (over land) at nadir
Cloud Base Height	10 km at nadir
Cloud Cover/Layers	25 km at nadir
Cloud Effective Particle Size	5 km at nadir
Cloud Optical Thickness/Transmittance	5 km at nadir
Cloud-Top Height	5 km at nadir
Cloud-Top Pressure	5 km at nadir
Cloud-Top Temperature	5 km at nadir
Active Fires	0.75 km at nadir
Albedo (Surface)	0.75 km at nadir
Land Surface Temperature	0.75 km at nadir
Soil Moisture	0.75 km at nadir
Surface Type	1 km at nadir
Vegetation Index	0.38 km at nadir

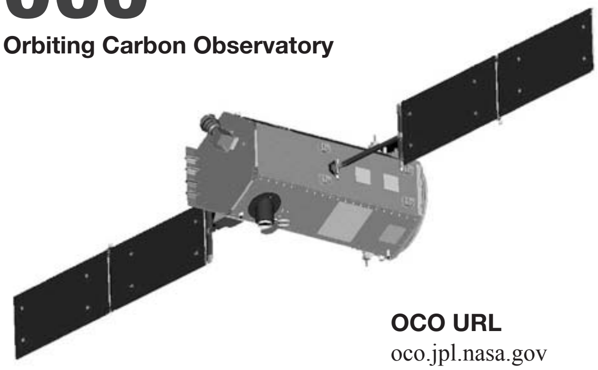
NPP Data Products

Product Name	Spatial Resolution
VIIRS *(cont.)*	
Sea Surface Temperature*	0.75 km at nadir
Ocean Color and Chlorophyll	0.75 km at nadir
Net Heat Flux	20 km at nadir
Sea Ice Characterization	0.8 km at nadir
Ice Surface Temperature	10 km at nadir
Snow Cover and Depth	0.8 km at nadir

NPP Data Products

OCO

Orbiting Carbon Observatory



OCO URL
oco.jpl.nasa.gov

Key OCO Facts

Spacecraft: Orbital Sciences LeoStar-2

Orbit
Type: Near-polar, sun-synchronous
Ascending Node: 1:18–1:33 p.m..
Altitude: 705 km
Inclination: 98.2° ± 0.1°
Period: 98.8 minutes
Repeat Cycle: 16 day

Dimensions: 2.3-m long × 1.4-m diameter (stowed for launch)

Mass: < 530 kg (wet, spacecraft bus + observatory + fuel)

Power: 786 W (orbit average, end of life)

Design Life: 2 years

Data Links: X-Band @ 150 Mbps

Telemetry: S-Band @ 2 Mbps

Summary

OCO will provide space-based global measurements of atmospheric carbon dioxide (CO_2) with the precision and resolution needed to identify and characterize the processes that regulate this important greenhouse gas. Data collected by OCO will be combined with meteorological observations and ground-based CO_2 measurements to help characterize CO_2 sources and sinks on regional scales at monthly intervals for 2 years.

Instruments

- Three high-resolution grating spectrometers

Points of Contact

- *OCO Principal Investigator:* David Crisp, NASA Jet Propulsion Laboratory/California Institute of Technology
- *OCO Deputy Principal Investigator:* Charles E. Miller, NASA Jet Propulsion Laboratory/California Institute of Technology

Other Key Personnel

- *OCO Program Scientist:* Phil DeCola, NASA Headquarters
- *OCO Program Executive:* Eric Ianson, NASA Headquarters
- *OCO Project Manager:* Rod Zieger, NASA Jet Propulsion Laboratory/California Institute of Technology

Mission Type

Earth Observing System (EOS) Exploratory Measurements (Earth System Science Pathfinder)

Launch

- *Date and Location:* No earlier than 2008, from Vandenberg Air Force Base, California
- *Vehicle:* Taurus 3110 rocket

Relevant Science Focus Area

(see NASA's Earth Science Program section)

- Atmospheric Composition
- Carbon Cycle, Ecosystems, and Biogeochemistry

Related Applications

(see Applied Sciences Program section)

- Air Quality
- Carbon Management
- Public Health

OCO Science Goals

- Collect space-based measurements of atmospheric carbon dioxide (CO_2) with the precision, resolution, and coverage needed to improve our understanding of the geographic distribution of CO_2 sources and sinks (surface fluxes) and the processes controlling their variability on seasonal time scales.
- Validate a passive spectroscopic measurement approach and analysis concept that is well suited for future systematic CO_2 monitoring missions.

OCO Mission Background

CO_2 is produced every time we start a car, light a fire, or exhale. These and other human activities have increased the atmospheric concentration of this greenhouse gas by about 25% since the dawn of the industrial age, raising concerns about climate change. Our ability to predict future changes in atmospheric CO_2 concentration, and its impact on climate is hampered by limitations in our understanding of the role of CO_2 in the terrestrial carbon cycle. Precise ground-based measurements collected since the 1950s indicate that only about half of the CO_2 emitted into the atmosphere by fossil-fuel combustion has remained there. The oceans and land biosphere have apparently absorbed the rest of the CO_2. But the question is, where? Unfortunately, available measurements do not have the spatial and temporal resolution and coverage needed to determine where all of the CO_2 sinks are located or what controls their behavior. This precludes accurate predictions of how the behavior of these CO_2 sinks might evolve over time as the climate changes and thus complicates efforts to predict future CO_2 increases and their effects on the climate.

Carbon-cycle modeling studies indicate that global, space-based observations of the column-averaged CO_2 dry-air mole fraction (X_{CO2}) could dramatically improve our understanding of the environmental processes that control the atmospheric CO_2 budget. Precise measurements of X_{CO2} are needed for this application because carbon-cycle inverse models infer surface-atmosphere CO_2 fluxes from small spatial and temporal variations in this quantity. These models show that X_{CO2} measurements with precisions near 0.3% (~1 part per million (ppm) out of the ambient ~370 ppm CO_2 concentration) are needed to identify and characterize surface CO_2 sources and sinks on regional-to-continental spatial scales and seasonal time scales.

OCO will make the first space-based measurements of atmospheric CO_2 with the precision, resolution, and coverage needed to characterize the geographic distribution of CO_2 sources and sinks and quantify their variability**.** During its two-year mission, OCO will fly in a sun-synchronous polar orbit that provides near-global coverage of the sunlit portion of Earth with a 16-day repeat cycle. The observatory carries a single instrument that incorporates three high-resolution grating spectrometers, designed to measure the near-infrared absorption by CO_2 and molecular oxygen (O_2) in reflected sunlight. The orbit's early-afternoon equator crossing time maximizes the available signal and minimizes diurnal biases in CO_2 measurements associated with photosynthesis. Large numbers of coincident CO_2 and O_2 soundings will be obtained at high spatial resolution to reduce the impact of random errors and minimize biases associated with clouds and other sources of spatial inhomogeneity within each measurement footprint.

Remote-sensing retrieval algorithms will be used to process the CO_2 and O_2 measurements to estimate X_{CO2} in each sounding. Independent calibration and validation approaches will be used to identify and correct regional-scale (1000 km × 1000 km) biases in the space-based X_{CO2} measurements. These validation methods include ground-based measurements of X_{CO2} obtained with upward-looking spectrometers as well as *in situ* measurements of CO_2 from aircraft, towers, and the existing ground-based network, with all validation measurements tied to an established CO_2 calibration standard. Once validated, the space-based X_{CO2} measurements will be combined with other environmental data in sophisticated carbon-cycle models to characterize CO_2 sources and sinks on regional scales at monthly intervals over two annual cycles.

Measurement Approach

High-resolution spectroscopic observations of reflected sunlight in the near-infrared (NIR) CO_2 absorption bands are ideal for retrieving X_{CO2} because they provide high sensitivity near the surface, where most CO_2 sources and sinks are located. The weak CO_2 band near 1.61 μm was selected for CO_2 column measurements because this spectral region is relatively free of absorption by other gases, and the observed absorption is most sensitive to the CO_2 concentration near the surface.

Bore-sighted measurements in the 0.76-μm O_2 A-band provide direct constraints on the total (dry-air) atmospheric pressure of the reflecting surface. This information must be combined with the CO_2 column estimates to derive X_{CO2}. Aircraft studies show that A-band observations can provide surface-pressure estimates with accuracies of ~1 millibar (O'Brien and Mitchell, 1992). A-band spectra also provide a sensitive indicator of clouds and optically thick aerosols, which preclude full-column measurements of CO_2.

Spectra of the strong 2.06-μm band provide independent constraints on the aerosol optical properties at near-infrared wavelengths, dramatically improving the accuracy of X_{CO2} retrievals in aerosol-laden conditions. Bore-sighted measurements in this band also provide direct constraints on the atmospheric temperature and humidity along the optical path, minimizing systematic errors associated with uncertainties in these parameters. A single 'sounding' consists of bore-sighted spectra in the 0.76-μm O_2 A-band and the CO_2 bands at 1.61 μm and 2.06 μm.

The spectral range of each channel includes the complete molecular absorption band as well as some nearby continuum to provide constraints on the optical properties of the surface albedo and aerosols. The spectral resolving power for each channel was selected to maximize the sensitivity to variations in the column abundances of

CO_2 and O_2 and to minimize the impact of systematic measurement errors. A spectral resolving power, $\lambda/\Delta\lambda > 20,000$ separates individual CO_2 lines in the 1.61- and 2.06-μm regions from weak H_2O and CH_4 lines and from the underlying continuum. For the O_2 A-band, a resolving power of ~17,000 is needed to distinguish the O_2 doublets from the continuum. With these resolving powers, the OCO retrieval algorithm can characterize the surface albedo throughout the band and solve for the wavelength dependence of the aerosol scattering, minimizing X_{CO2} retrieval errors contributed by uncertainties in the continuum level.

Spatial and Temporal Sampling Approach

The primary advantage of space-based X_{CO2} measurements is their global coverage and dense spatial sampling. OCO will fly at the front of the Earth Observing System (EOS) Afternoon Constellation (A-Train), about 15 minutes ahead of the Aqua platform. OCO will have a 1:15-p.m. equator crossing time and will share its ground track with Aqua. This local time of day is ideal for spectroscopic observations of CO_2 in reflected sunlight because the Sun is high, maximizing the measurement signal-to-noise ratio, and because the CO_2 concentrations are near their diurnally-averaged values at this time of day. This orbit also facilitates direct comparisons of OCO observations with measurements taken by Aqua, Aura, and other A-Train missions. The orbit's 16-day repeat cycle facilitates monitoring X_{CO2} variations on semi-monthly intervals.

While many X_{CO2} soundings are needed to adequately characterize the CO_2 variations on regional scales, contiguous spatial sampling is not required because CO_2 is transported over a large area as it is mixed through the atmospheric column. However, the full atmospheric column must be sampled to provide constraints on surface CO_2 sources and sinks. Clouds and optically thick aerosols preclude measurements of the complete column. Large topographic variations and other sources of spatial inhomogeneity within individual soundings can also introduce systematic biases that can compromise the accuracy of X_{CO2} retrievals.

To obtain enough useful soundings to accurately characterize the X_{CO2} distribution on regional scales, even in the presence of patchy clouds, the OCO instrument continuously records 4 soundings along a 0.4°-wide cross-track swath at 3 Hz, yielding 12 soundings/s. As the spacecraft moves along its ground track at 6.78 km/s, each sounding will have a surface footprint with dimensions of ~1.29 km × 2.25 km at nadir, and ~196 soundings are recorded over each 1°-latitude increment along the orbit track.

OCO will collect science observations in Nadir, Glint, and Target modes. The same data sampling rate (12 soundings/s) is used in all three modes. In Nadir mode, the satellite points the instrument to the local nadir, so that data can be collected along the ground track just below the spacecraft. Science observations will be collected at all latitudes where the solar zenith angle is less than 85°. This mode provides the highest spatial resolution on the surface and is expected to return more usable soundings in regions that are partially cloudy or have significant surface topography. However,

Key OCO Instrument Facts

Heritage: The OCO instrument and measurement approach are new. However, key instrument components (optical approach, holographic grating, cryocooler, detectors) have been flight qualified for other missions, including the Total Ozone Mapping Spectrometer (TOMS), Atmospheric Infrared Sounder (AIRS), and Tropospheric Emission Spectrometer (TES).

Instrument Type: Three high-resolution grating spectrometers

Sampling Modes: Nadir, glint, and target (see text for details)

Spectral Range: 3 spectral channels (see table)

Standard Profile Spacing: 2.25 km (downtrack) × 1.29 km (crosstrack)

Spatial Resolution: 1.29 km × 2.25 km

Spectral Range and Resolving Power of Bands:

Minimum Wavelength
- O_2 A-Band: 0.758 μm
- Weak CO_2: 1.594 μm
- Strong CO_2: 2.042 μm

Maximum Wavelength
- O_2 A-Band: 0.772 μm
- Weak CO_2: 1.619 μm
- Strong CO_2: 2.082 μm

Resolving Power ($\lambda/\Delta\lambda$)
- O_2 A-Band: > 17,000
- Weak CO_2: > 20,000
- Strong CO_2: > 20,000

Dimensions: 1.6 m × 0.4 m × 0.6 m

Mass: < 150 kg

Power: < 165 W

Thermal Control: Active cryocooler and radiators

System Temperature:
- Optics: 268–273 K
- Detectors: 120–180 K

Field of View (FOV): 14-mrad wide cross-track swath

IFOV: ~0.09 mrad (single pixel)

Incidence Angle: Nadir, sun glint, or targeting of a stationary surface site these nadir observations may not provide adequate signal to noise over dark ocean surfaces.

The Glint mode was designed to address this concern. In this mode, the spacecraft points the instrument toward the bright 'glint' spot, where solar radiation is specularly reflected from the surface. Glint measurements should provide much higher signal-to-noise ratios over the ocean. Glint soundings will be collected at all latitudes where the local solar zenith angle is less than 75°. OCO will switch from Nadir to Glint modes on alternate 16-day global ground-track repeat cycles so that the entire Earth is mapped in each mode on roughly monthly time scales.

Finally, Target mode will be used to observe specific stationary surface targets as the satellite flies overhead. A Target track pass can last for up to 9 minutes, providing more than 6,480 samples over a given site at emission angles between 0° and ±85°. Target Track passes will be conducted over each OCO validation site at monthly intervals.

Validation Program

The OCO team is currently developing techniques to verify the accuracy of the space-based X_{CO2} measurements acquired from space. The validation program is based on measurements of X_{CO2} from a network of ground-based, solar-looking, Fourier Transform Spectrometers that obtain nearly continuous observations throughout the sunlit portion of the day, in the same spectral regions as the space-based grating spectrometers. The OCO project will also use *in situ* observations of the CO_2 mixing ratio from flasks, continuous sensors, tall towers, and aircraft. Precise laboratory instruments will determine the strengths, widths, and positions of the absorption lines to the level of precision required for proper interpretation of the atmospheric spectroscopic measurements. Research scientists will employ all of these sources of information to calibrate, verify, and improve the accuracy of the space borne OCO X_{CO2} measurements.

OCO Partners

NASA JPL leads the OCO project and is developing the science data system for the mission. Two primary partners are working with JPL. Orbital Sciences Corporation is responsible for manufacturing the spacecraft and for launch and ground operations, while Hamilton Sundstrand Sensor Systems is building the instrument.

OCO Instrument Technical Details

The observatory carries a single instrument that incorporates three high-resolution grating spectrometers, fed by a common telescope. Spatially resolved spectroscopic measurements of reflected sunlight in near infrared CO_2 and molecular oxygen (O_2) bands are used to retrieve X_{CO2}:

Key OCO Instrument Facts

(cont.)

Duty Cycle: On continuously, but science data are recorded only over the sunlit hemisphere.

Data Rate: ~1 mbps for 54 min each orbit

Transmission Frequency: X-band downlink, S-band uplink

Repeat Cycle: 16 days

Sampling Interval: 12–24 samples/s

Accuracy: Single sounding X_{CO2} accuracy of better than 2%, regional-scale X_{CO2} accuracy of 0.3% on monthly time scales

Calibration:

Absolute Radiometric: Diffuse solar spectrum transmitted through the entire optical system.

Relative Radiometric: Lamp 'flat fields' reflected from diffuser plate within each channel and diffuse solar observations for channel-to-channel.

Spectral Wavelength: Measurement of absorption-line positions in routine science observations.

Spectral Line Shape: Solar lines and high-altitude atmospheric lines observed with limb views.

Pointing: Bright stars observed to identify static pointing errors.

- The CO_2 column abundance is inferred from high-spectral-resolution ($\lambda/\Delta\lambda$ ~20,000) observations of the weak CO_2 band near 1.61 μm;

- Bore-sighted, high-spectral-resolution ($\lambda/\Delta\lambda$ ~17,000) measurements of the 0.76-μm O_2 A-band are used to infer the total atmospheric mass (surface pressure), and to assess the effects of clouds, aerosols, and surface topography on the photon path-length distribution;

- High-spectral-resolution ($\lambda/\Delta\lambda$ ~20,000) measurements in the strong CO_2 band near 2.06 μm provide additional constraints on the CO_2 column abundance and the effects of aerosols on the photon path length.

OCO Data Products

Product Name or Grouping	Processing Level	Coverage	Spatial/Temporal Characteristics
OCO Instrument			
Calibrated Radiance–Spectra of O_2 A-band, 1.61-and 2.06-μm CO_2 bands	1B	Atmospheric Column	1.29 km × 2.25 km horizontal resolution/ 16 days
Column-Averaged Dry-Air Mole Fraction, X_{CO2}	2	Atmospheric Column	1.29 km × 2.25 km horizontal resolution/ 16 days

OCO Data Products

OSTM

Ocean Surface Topography Mission

OSTM URLs
sealevel.jpl.nasa.gov/mission/ostm.html
www.aviso.oceanobs.com/

Note on Mission Name: The French have referred to this mission as Jason-2, since it is a follow-on mission to Jason. However, NASA is using the name OSTM and therefore, that name will be used in this entry. The only exception is where the position titles of French scientists involved in the mission are listed.

Summary

OSTM, a continuation of the TOPEX/Poseidon and Jason missions, is based on the science and pre-operational returns of these two missions and will support global and regional operational applications. Like its predecessors, OSTM will map ocean surface topography and the data collected will provide information on ocean surface current velocity and heights which, when combined with ocean models, can lead to a four-dimensional description of ocean circulation. Data from OSTM will extend the time series of ocean surface topography measurements for detecting previously unknown changes on decadal scales, increase understanding of ocean circulation, improve forecasting of climate events, and measure global sea level change.

Instruments

- Advanced Microwave Radiometer (AMR)
- Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) satellite tracking system
- GPS Payload receiver (GPSP)
- Laser Retroreflector Array (LRA)
- Poseidon-3 altimeter

Key OSTM Facts

Joint with NOAA, CNES, and EUMETSAT

Orbit
Type: Circular, non-sun-synchronous
Descending Node: N/A
Altitude: 1336 km
Inclination: 66°
Period: 112.4 minutes
Repeat Cycle: 9.9156 days

Dimensions
Platform module: 95.4 cm × 95.4 cm × 100.0 cm
Payload module: 95.4 cm × 95.4 cm × 121.8 cm
Solar array span: Two wings with four 1.5 m × 0.8 m panels per wing

Mass: 500 kg

Power: 580 W

Downlink: S-Band to JPL, Wallops Island, Virginia, Poker Flats, Alaska, Aussaguel, France, and a site in Germany

Design Life: 3-year primary mission; 2-year extended mission

Contributors: NASA, NOAA, Centre National d'Etudes Spatiales (CNES), European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT)

Points of Contact

- *U.S. OSTM Project Scientist:* Lee-Lueng Fu, NASA Jet Propulsion Laboratory/California Institute of Technology
- *French OSTM Project Scientist:* Yves Menard, CNES Toulouse Space Center

Other Key Personnel

- *OSTM Program Scientist:* Eric Lindstrom, NASA Headquarters
- *OSTM Program Executive:* Steve Neeck, NASA Headquarters
- *OSTM Project Manager:* Parag Vaze, NASA Jet Propulsion Laboratory/California Institute of Technology
- *OSTM Program Manager:* Mike Mignogno, NOAA NESDIS
- *OSTM Project Manager:* Walid Bannoura, NOAA NESDIS

- *OSTM Program Manager:* Mikael Rattenborg, EUMETSAT
- *Jason-2 Program Manager:* Eric Thouvenot, CNES Toulouse Space Center
- *Jason-2 Project Manager:* Jacqueline Perbos, CNES Toulouse Space Center

Mission Type

Next Generation Systematic Measurements

Launch

- *Date and Location:* No earlier than June 2008, from Vandenberg Air Force Base, California

Relevant Science Focus Areas

(see NASA's Earth Science Program section)

- Climate Variability and Change
- Water and Energy Cycles

Related Applications

(see Applied Sciences Program section)

- Coastal Management
- Disaster Management

OSTM Science Goals

OSTM will continue to satisfy the following science goals of the ocean surface topography effort:

- Determine general ocean circulation and understand its role in Earth's climate, particularly how ocean circulation impacts Earth's hydrological and biogeochemical cycles.
- Study the variation of ocean circulation on time scales ranging from seasonal and annual to decadal and examine how this variation impacts climate change.
- Collaborate with other global ocean-monitoring programs to produce routine models of the global ocean for scientific and operational applications.
- Study large-scale ocean tides.
- Study geophysical processes and their effects on ocean surface topography.

OSTM Instruments

AMR
Advanced Microwave Radiometer

AMR is a three-frequency microwave radiometer that measures total water vapor along the path viewed by the altimeter and is used for range correction. It measures brightness temperatures in the nadir column at 18.7, 23.8, and 34 GHz.

DORIS
Doppler Orbitography and Radiopositioning Integrated by Satellite

DORIS is a precision orbit determination system that provides orbital positioning information. An onboard receiver accurately measures the Doppler shift on both transmitted frequencies (401.25 and 2.036 GHz) received from an orbit determination beacon (ODB) station.

GPSP
GPS Payload receiver

GPSP will be a high performance GPS receiver designed to provide tracking data for precise orbit determination of the OSTM spacecraft. It is derived from the TRSR (Turbo Rogue Space Receiver) flown on Jason. It will measure precision GPS code phase and continuous carrier phase data from up to 12 GPS satellites.

LRA
Laser Retroreflector Array

As on TOPEX/Poseidon and Jason, the OSTM LRA will be used to calibrate the other location systems on the satellite with a very high degree of precision. LRA is a totally passive reflector designed to reflect laser pulses back to their point of origin on Earth. It consists of nine suprasil quartz retroreflectors arranged to provide a near-hemispherical response.

Poseidon-3

Poseidon-3 is a next generation dual-frequency radar altimeter. It is an improved version of Poseidon-2, the dual-frequency radar altimeter flown on Jason.

OSTM Mission Background

OSTM will provide continuity of ocean topography measurements beyond TOPEX/Poseidon and Jason. This mission will continue the critically important multi-decadal record of ocean topography measurements for ocean circulation and climate studies. The systematic measurements obtained by OSTM will provide required knowledge to answer key NASA science questions and help scientists observe, understand, and model the Earth system to learn how it is changing, and the consequences for life on Earth.

The instruments on OSTM are either identical to or slightly improved versions of those flown on Jason. OSTM will use the same measurement approach as Jason, and will be developed and operated as a four-party international collaboration among NASA, NOAA, CNES, and EUMETSAT. After the OSTM mission is complete, the intent is that the operational community will assume responsibility for future sea surface topography measurements.

Otherwise, the OSTM mission background is the same as Jason. Please see the Jason entry for complete details.

AMR

Advanced Microwave Radiometer

AMR is an enhanced version of the Jason Microwave Radiometer (JMR)—see Jason entry for complete description. It offers virtually the same capabilities as JMR but is smaller, consumes less power, and has a faster data rate. JPL has overall responsibility for AMR management, system design, electronics development, integration and test, and calibration.

DORIS

Doppler Orbitography and Radiopositioning Integrated by Satellite

The DORIS instruments slated for the OSTM mission are upgraded versions of those aboard Jason—see Jason entry for complete description of DORIS. Experience with SPOT-2, SPOT-4, TOPEX/Poseidon, and Jason has shown that the instrument operates most efficiently at altitudes between 750 and 1,500 km. However, DORIS can operate at altitudes from 300 km to several thousand km.

Key AMR Facts

Heritage: TOPEX/Poseidon, Seasat, Nimbus-7

Instrument Type: Three-channel microwave radiometer

Scan Type: Fixed pencil-beam spatially collocated with the nadir-pointing Poseidon-3 altimeter beam

Channel Center Frequencies: 18.7, 23.8, and 34.0 GHz

Channel Bandwidths: 200, 400, and 700 MHz

Antenna Half-Power Beamwidth: 1.8°, 1.4°, and 1.0°

Dimensions:
- Antenna: 1-m offset feed parabola
- Electronics module: 11 cm × 16 cm × 16 cm (primary and redundant)

Mass: 16 kg

Power: 15 W

Data Rate: 2.5 kbps (maximum)

Thermal Control: Electronics thermal control provided by passive radiator to space

Thermal Operating Range: 0° to 40° C (for electronics)

Radiometric Resolution: < 0.25 K

Absolute Calibration Accuracy: ±1 K

Contributors: NASA JPL (responsible center, instrument design)

Key DORIS Facts

Heritage: SPOT-2, TOPEX/Poseidon, SPOT-3, SPOT-4, Envisat, Jason

Instrument Type: Precision Orbit Determination System

Dimensions:
- Receiver Package: 31 cm × 35 cm × 17 cm (Dual receivers + Ultra Stable Oscillator)
- Antenna: 37 cm height × 16 cm diameter cone

Mass:
- Receiver Package: 17.9 kg
- Antenna: 2 kg

Power: 21 W

Duty Cycle: 100%

Data Rate: 330 bps

Thermal Control: Heat transfer by conduction to mounting surface and by radiation within the instrument module

GPSP

GPS Payload receiver

GPSP is essentially a slightly enhanced version of the Turbo Rogue Space Receiver (TRSR) on Jason. The description of GPSP is essentially identical to that of the TRSR found in the Jason entry. NASA's Jet Propulsion Laboratory at the California Institute of Technology will design and test the GPSP hardware, software, and ground support equipment. Spectrum Astro, Inc. will construct and test the GPSP flight unit.

GPSP URL

sealevel.jpl.nasa.gov/technology/instrument-gps.html

LRA

Laser Retroreflector Array

The LRA on OSTM is identical to the LRA on Jason. See the Jason entry for a detailed description of LRA.

Poseidon-3

Poseidon-3 is an enhanced version of the Poseidon-2 radiometer described in detail in the Jason entry. The microprocessor on Poseidon-3 (DSP 21020) is updated from Poseidon-2. Poseidon-3 also has an adaptive acquisition window based on the Doris/Diode on board. A land elevation model is also programmed in to improve Poseidon-3's ability to track coastal and land areas.

Poseidon-3 URL

www.aviso.oceanobs.com/html/missions/jason2/instruments/poseidon3_uk.html

Key DORIS Facts *(cont.)*

Thermal Operating Range: -10° to 50° C

FOV: 125° cone (centered on nadir)

Pointing Requirements (platform + instrument, 3σ):
- Control: 1.5°
- Knowledge: 0.2° (depending on the distance between the antenna phase center and the satellite center of mass)

Contributors: CNES (responsible center), THALES (instrument), SMP (ground beacons)

Key GPSP Facts

Heritage: Blackjack GPS receiver (Shuttle Radar Topography Mission, Jason)

Instrument Type: GPS Receiver and antenna

Dimensions:
- Receiver: 18 cm × 18 cm × 11 cm
- Antenna: 10.5-cm height × 30-cm diameter

Mass:
- Receiver: 2.5 kg
- Antenna: 1 kg
- Total: 7 kg (Dual-string configuration)

Power: 14W @ 28 V

Duty Cycle: 100%

Data Rate: 800 bps

Thermal Control: Heat transfer by conduction to mounting surface and by radiation within the instrument module

Thermal Operating Range: -10° to 50° C

Pointing Requirements (platform + instrument, 3σ):
- Control: 5°
- Knowledge: 5°

Contributors: JPL (responsible center); Spectrum Astro (instrument)

Key LRA Facts

Heritage: TOPEX/Poseidon, Jason

Function: Laser-tracking targets

Wavelengths: 532 nm (primary), 1064 nm (secondary)

Configuration: 9 corner cubes: 1 nadir looking, 8 arrayed azimuthally in truncated cone

FOV: 110º w/1.5 arcsec dihedral angle per cube

OSTM References

Escudier P., G. Kunstmann, F. Parisot, R. Boain, T. Lafon, P. Hoze, and S. Kaki, 2000: Jason System Overview and Status. AVISO Newsletter, Altimetry Edition, No. 7.

Mitchum G., R. Cheney, L. L. Fu, C. Le Provost, Y. Menard, and P. Woodworth, 2001: The future of sea surface height observations. In *Observing the Oceans in the 21st Century*, ed. by C. J. Koblinsky and N. R. Smith, GODAE and Bureau of Meteorology, Melbourne, Australia.

Key LRA Facts *(cont.)*

Dimensions: Each cube is 163-mm diameter × 66-mm height

Mass: 0.8 kg

Duty Cycle: 100%

Thermal Operating Range: -65° to 95° C

Contributors: NASA (responsible center), ITE Inc. (instrument)

Key Poseidon-3 Facts

Heritage: Poseidon-2 radar altimeter (Jason); Synthetic Aperture Interferometric Radar Altimeter–SIRAL (CryoSat)

Instrument Type: Dual-frequency radar altimeter (Ku-band and C-band)

Scan Type: Fixed nadir-pointing beam

Transmitted Pulse Width: 105 s

Pulse Repetition Frequency: 2100 Hz (1800 Hz for Ku-band and 300 Hz for C-band)

Maximum Radio-Frequency Output Power to Antenna: 38.5 dBm (Ku-band); 44 dBm (C-band)

Transmission Frequency: 13.575 GHz (Ku-band), 5.3 GHz (C-band)

Dimensions:
- Radio Frequency Unit (RFU): 42.2 cm × 24.6 cm × 24.5 cm
- Power Control (PC) Unit: 26.8 cm × 20.5 cm × 24.9 cm

Mass: 52 kg (dual-frequency, dual configuration with one antenna)

Power: 70 W (50 V for RFU, 20 V for PCU)

Duty Cycle: 100%

Data Rate: 22.5 kbps (including waveform data and onboard estimated parameters)

Thermal Control: Heat transfer by conduction to mounting surface and by radiation within the instrument module

Thermal Operating Range: -5° to 35° C

Pointing Requirements (platform + instrument, 3σ):
- Control (Satellite): 0.33°
- Knowledge: < 0.1°

Contributors: CNES (responsible center), Alcatel Space Industries (prime contractor)

OSTM Data Products

NOAA and EUMETSAT will distribute Operational Geophysical Data Records (OGDR) and Interim Geophysical Data Records (IGDR). NOAA and CNES will distribute Geophysical Data Record (GDR) products.

Product Name or Grouping	Processing Level	Coverage	Spatial/Temporal Characteristics
AMR, DORIS, GPSP, LRA, Poseidon-3			
Operational Geophysical Data Record	2	Global	66° N – 66° S latitude/every 10 days
Interim Geophysical Data Record	2	Global	66° N – 66° S latitude/delivered daily (latency 1–3 days)
Geophysical Data Record	2	Global	66° N – 66° S latitude/every 10 days

OSTM Data Products

QuikSCAT

QuikSCAT URL
winds.jpl.nasa.gov/

Summary

QuikSCAT acquires accurate, high-resolution, continuous, all-weather measurements of global (land, ice, and ocean) radar cross-sections and near-surface vector winds over the ice-free global oceans. The wind measurements are used for research investigations as well as in operational weather prediction. Radar cross-sections from land and ice-covered regions are used for vegetation classification/ monitoring, cryospheric investigations, and operational ice-edge and iceberg detection and monitoring.

Instrument

- SeaWinds

Points of Contact

- *SeaWinds Principal Investigator:* Michael Freilich, Oregon State University
- *QuikSCAT Project Scientist:* W. Timothy Liu, NASA Jet Propulsion Laboratory/California Institute of Technology

Other Key Personnel

- *QuikSCAT Program Scientist:* Eric Lindstrom, NASA Headquarters
- *QuikSCAT Program Executive:* Lou Schuster, NASA Headquarters
- *QuikSCAT Project Manager:* Rob Gaston, NASA Jet Propulsion Laboratory/California Institute of Technology

Mission Type

Earth Observing System (EOS) Systematic Measurements

Key QuikSCAT Facts

Spacecraft: Ball Aerospace BCP 2000 QuikBird Bus (variant)

Orbit
Type: Sun-synchronous
Equatorial Crossing: 6:00 p.m.
Altitude: 803 km
Inclination: 98.6°
Period: 101 minutes

Dimensions: Main spacecraft bus is 2.2 m × 1.7 m × 1.4 m; radar extends 1.3 m from main spacecraft

Mass: 970 kg

Power: 874 W

Downlink: S-band, 262 kbps. Ground stations at Wallops Flight Facility Ground Station (WGS), Alaska Ground Station (in Poker Flats) (AGS), Svalbard Ground Station (SGS), and McMurdo Ground Station (MGS) designed to allow fully processed data products within three hours of measurement acquisition by the spacecraft, to enable operational applications such as weather and ice/marine hazard prediction.

Design Life: 3 years (exceeded)

Contributors

Ball Aerospace & Technologies Corp. (BATC): Integration and testing of total space segment—includes bus and instruments

Laboratory for Atmospheric and Space Physics (LASP), University of Colorado: Mission operations)

Honeywell: Antenna subsystem

Raytheon: Radio-frequency subsystem

NASA JPL: Command and data subsystem

Launch

- *Date and Location:* June 19, 1999, from Vandenberg Air Force Base, California

Relevant Science Focus Area

(see NASA's Earth Science Program section)

- Climate Variability and Change
- Weather

Related Applications

(see Applied Sciences Program section)

- Air Quality
- Coastal Management
- Disaster Management

QuikSCAT Mission Background

The QuikSCAT mission was developed rapidly following the premature demise of Japan's National Space Development Agency (NASDA) Advanced Earth Observation Satellite (ADEOS). QuikSCAT operated throughout the lifetime of the ADEOS-II mission (December 2002–October 2003), which carried an identical SeaWinds instrument, and beyond, still operating in early 2006.

SeaWinds

SeaWinds Background

SeaWinds is a Ku-band scatterometer with rotating antenna to measure global radar scattering cross-section and ocean near-surface wind velocity.

The SeaWinds instruments are designed to acquire accurate, high-resolution, continuous, all-weather measurements of global (land, ice, and ocean) radar cross-sections and near-surface vector winds over the ice-free global oceans. SeaWinds on QuikSCAT is crucial because it is the only instrument currently on orbit capable of measuring wind velocity—both speed and direction—under nearly all-weather conditions. SeaWinds data enable studies of tropospheric dynamics, upper-ocean circulation, and air-sea interaction. SeaWinds data are provided in near real time to NOAA's National Environmental Satellite, Data, and Information Service (NESDIS) and then are distributed nationally and internationally for routine use in global and regional operational weather and ice prediction.

SeaWinds transmits pulses of microwave radiation at 13.4 GHz and measures the backscattered signal from Earth over a continuous, 1800-km-wide swath centered on the subsatellite track. The surface normalized radar cross-section is calculated from the backscatter measurements and knowledge of the viewing geometry and instrument characteristics. Over the ocean, the received power results primarily from scattering from centimetric ocean roughness elements whose amplitudes and directional distributions are in equilibrium with the local wind; thus backscattered power varies as a function of wind speed and direction relative to the radar beam. Multiple, near-simultaneous measurements of normalized radar cross-sections obtained from the same location, but from different viewing directions and incidence angles, are combined with an empirical model function relating backscatter cross-section to wind conditions to allow calculation of near-surface wind speed and direction over the ice-free oceans.

With the failure of the ADEOS-II spacecraft on October 24, 2003, the SeaWinds instrument on QuikSCAT once again became the only space-based scatterometer in operation. The SeaWinds instrument builds on the heritage of the NASA scatterometer (NSCAT), which flew on ADEOS from August 1996 until the failure of the spacecraft in June 1997. The dual-scanning pencil-beam design of the SeaWinds instruments replaces the six, 3-m-long antenna array used for NSCAT with a single 1-m diameter rotating-dish antenna. This compact design allowed SeaWinds to

Key SeaWinds Facts

Heritage: SEASAT, NASA Scatterometer (NSCAT) Advanced Earth Observing Satellite (ADEOS)

Dimensions:

Computer and Data Subsystem: 32 cm × 46 cm × 34 cm

Scatterometer Electronics Subsystem: 81 cm × 91 cm × 43 cm

100-cm-diameter antenna dish on 60-cm diameter × 60-cm pedestal

Scatterometer Antenna Subsystem Total Height: ~150 cm

Mass: 220 kg

Power: 220 W

Duty Cycle: 100%

Data Rate: 40 kbps

Thermal Control: Radiators

Thermal Operating Range: 5–40° C

Field of View (FOV): Rotating (at 18 rpm) pencil-beam antenna with dual feeds pointing 40° and 46° from nadir

IFOV: ±51° from nadir (actual IFOV is 25 km × 35 km (ellipse) ±51° is total swath width.)

Swath: 1800 km (±51°) from 803-km altitude

Pointing Requirements (3σ):

Control: < 0.3° (~1000 arcsec)

Knowledge: < 0.05° (~167 arcsec)

Stability: < 0.008°/s (30 arcsec/s)

Contributor: NASA JPL

be accommodated on both the QuikSCAT and ADEOS-II spacecraft and also provides a contiguous measurement swath (eliminating the 329-km nadir gap in the NSCAT data).

SeaWinds acquires high-accuracy measurements of wind speed and direction over nearly 90% of the ice-free global oceans each day (exceeding the temporal-resolution requirements in the data product table found at the end of this section). SeaWinds measurements are provided in near real time to the Centers for Environmental Prediction (CEP), the European Centre for Medium-Range Weather Forecasts (ECMWF), and other meteorological agencies for use in marine forecasting, operational global numerical weather prediction, and climate forecasting. SeaWinds data play a crucial role in interdisciplinary scientific investigations of global weather patterns, marine meteorology, wind-driven ocean circulation, air-sea interaction, and climate dynamics. Raw backscatter measurements from land and ice are also used to classify vegetation type, monitor large-scale land use and productivity changes, and identify and monitor ice type and extent. Post-launch validation of the SeaWinds measurements showed that they exceeded the pre-launch science-accuracy requirements. Research studies and operational analyses using these data confirm the utility and impact of the scatterometer vector winds and demonstrate the scientific potential of the scatterometer measurements over land and ice. SeaWinds data products consist of global, multi-azimuth normalized radar-cross-section measurements with ~6-km × 25-km spatial resolution, and 25-km resolution ocean vector winds (~12% speed and 20° direction accuracies for wind speeds of 3–30 m/s under non-raining conditions) in the measurement swath.

SeaWinds URL

winds.jpl.nasa.gov/

QuikSCAT/SeaWinds References

Chelton, D. B., M. G. Schlax, M. H. Freilich, and R. F. Milliff, 2004: Satellite measurements reveal persistent small-scale features in ocean winds. *Science*, **303**, 978–983.

Ebuchi. N., H. C. Graber, and M. J. Caruso, 2002: Evaluation of wind vectors observed by QuikSCAT/SeaWinds using ocean buoy data. *J. Ocean. Atmos. Tech.*, **19**, 2049–2062.

Liu, W. T., 2002: Progress in scatterometer applications. *J. Oceanogr.*, **58**, 121–136.

Long, D. G., M. R. Drinkwater, B. Holt, S. Saatchi, and C. Bertoia, 2001: Global ice and land climate studies using scatterometer image data. *Eos, Trans. Amer. Geophys. Union*, **82**, 503. [EOS Electronic Supplement: www.agu.org/eos_elec/010126e.html]

Naderi, F. M., M. H. Freilich, and D. G. Long, 1991: Spaceborne radar measurement of wind velocity over the ocean—An overview of the NSCAT Scatterometer System. *Proc. IEEE*, **79**, 850–866.

Spencer, M. W., C. Wu, and D. G. Long, 1997: Tradeoffs in the design of a spaceborne scanning pencil-beam scatterometer: Application to SeaWinds. *IEEE Trans. Geosci. Remote Sens.*, **35**, 115–126.

Note: For additional references, see the ADEOS-II section.

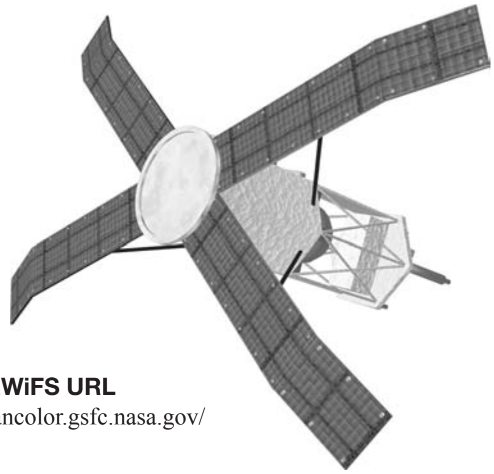
QuikSCAT Data Products

Product Name or Grouping	Processing Level	Coverage	Spatial/Temporal Characteristics
SeaWinds *Data Set Start Date: July 19, 1999*			
Normalized Radar Cross Section and Ancillary Data	1B	Global	6 km × 25 km horizontal resolution (hres)/ 70% daily and 90% every 2 days
Grouped and Surface-Flagged Backscatter and Attenuations	2A	Global	25 km × 25 km hres/70% daily and 90% every 2 days
Ocean Wind Vectors in 25-km Grid	2B	Oceans	25 km hres/90% every 2 days
Ocean Wind Vectors on regular, global latitude-longitude grid	3	Oceans	25 km hres/90% every 2 days

QuikSCAT Data Products

Orbview-2/SeaWiFS

OrbView-2 / Sea-viewing Wide Field-of-view Sensor



SeaWiFS URL
oceancolor.gsfc.nasa.gov/

Summary

The purpose of the SeaWiFS Mission is to provide quantitative data on global ocean bio-optical properties to the Earth science community. Subtle changes in ocean color signify various types and quantities of marine phytoplankton (microscopic marine plants), the knowledge of which has both scientific and practical applications.

Instruments

- Sea-viewing Wide Field-of-view Sensor (SeaWiFS)

Points of Contact

- *SeaWiFS Project Scientist:* Chuck McClain, NASA Goddard Space Flight Center
- *SeaWiFS Project Manager:* Gene Feldman, NASA Goddard Space Flight Center

Mission Type

Earth Observing System (EOS) Systematic Measurements

Launch

- *Date and Location:* August 1, 1997, from Vandenberg Air Force Base, California
- *Vehicle:* Pegasus XL launch vehicle from a Lockheed L-1011 aircraft

Key Orbview-2/SeaWiFS Facts

Orbit:
Type: Sun-synchronous
Altitude: 705 km
Equatorial Crossing: Noon ± 20 mins
Inclination: 98.2°
Period: 99 minutes

Design Life: 5 years

Operating Status: Operational

Relevant Science Focus Areas

(see NASA's Earth Science Program section)

- Carbon Cycle, Ecosystems and Biogeochemistry
- Climate Variability and Change
- Water and Energy Cycles

Related Applications

(see Applied Sciences Program section)

- Carbon Management
- Coastal Management

OrbView-2/SeaWiFS Science Goal

The purpose of SeaWiFS data is to examine oceanic factors that affect global change and to assess the oceans' role in the global carbon cycle, as well as other biogeochemical cycles, through a comprehensive research program. The SeaWiFS Project aims to obtain accurate ocean color data from the world's oceans, to process these data in conjunction with ancillary data into meaningful biological parameters, such as photosynthesis rates, and to make these data readily available to researchers.

OrbView-2/SeaWiFS Mission Background

The oceanographic community considers ocean-color data critical for the study of ocean primary production and global biogeochemistry. 'Primary production' refers to the organic material in the sea that is produced by primary producers. These primary producers, i.e., algae and some bacteria, exist at the lowest levels of the food chain and use sunlight or chemical energy, rather than other organic material, as sources of energy. It is thought that marine plants remove carbon from the atmosphere at a rate equivalent to terrestrial plants, but knowledge of interannual variability is very poor.

The concentration of microscopic marine plants, called phytoplankton, can be derived from satellite observation and quantification of ocean color. This is because the color in most of the world's oceans in the visible light region (400–700 nm) varies with the concentration of chlorophyll and other plant pigments present in the water, i.e., the more phytoplankton present, the greater the concentration of plant pigments and the greener the water.

OrbView-2 (OV-2—formerly known as SeaStar) is a satellite system developed by Orbital Science Corporation. It carries NASA's Sea-viewing Wide Field-of-view Sensor (SeaWiFS) as its only instrument. OV-2's orbit allows SeaWiFS to acquire approximately 15 pole-to-pole swaths of data per day, and approximately 90% of the ocean surface is scanned every two days.

SeaWiFS ocean-color data thus constitute a valuable resource for determining the abundance of ocean biota on a global scale. The data can also be used to assess the ocean's role in the global carbon cycle and the exchange of other critical elements and gases between the atmosphere and the ocean.

History

SeaWiFS is a follow-on sensor to the Coastal Zone Color Scanner (CZCS), which ceased operations in 1986. In the first arrangement of its kind, the U.S. Government procured space-based environmental remote-sensing data for research purposes from a commercial operator. Orbital Sciences Corporation (OSC) built and launched the SeaStar satellite carrying SeaWiFS on August 1, 1997. Following launch, the satellite's name was changed to OrbView-2 and operations were turned over to ORBIMAGE, a spin-off of OSC. ORBIMAGE markets the data for commercial and operational use. OV-2 is not provided by or operated by NASA. NASA purchases the data.

SeaWiFS data have been used to help clarify the magnitude and variability of chlorophyll and primary production by marine phytoplankton and to determine the distribution and timing of spring blooms, i.e., the time of highly abundant growth. The scientific and technical experience gained in the SeaWiFS mission provided valuable preparation for the design and application of the Earth Observing System's Moderate Resolution Imaging Spectroradiometer (MODIS) instruments flying on both Terra and Aqua and also for future sensors such as the Visible Infrared Imaging Radiometer Suite (VIIRS) on the National Polar-orbiting Operational Environmental Satellite System (NPOESS).

SeaWiFS

The SeaWiFS instrument has scanning mechanisms to drive an off-axis folded telescope and a rotating half-angle mirror. Incoming scene radiation is collected by the folded telescope and reflected onto the rotating half-angle mirror. The collected radiation is then relayed through dichroic beam splitters to separate the radiation into four wavelength intervals—each wavelength interval encompassing two of the eight SeaWiFS spectral bands. Four corresponding aft-optics direct the radiation in the four separate wavelength intervals through two separate spectral band-pass filters that further separate the radiation into eight SeaWiFS spectral bands. The aft-optics assemblies also image each of the resultant defined bands of radiation onto four detectors that are aligned in the scan direction. Monitoring of sensor calibration over periods of a few orbits, to several months or years, is accomplished using solar calibration for the former and lunar calibration for the latter. Solar calibration uses a solar-radiation diffuser and an input port located in a fixed position outside of the 58.3º SeaWiFS scene-scan interval. Lunar calibration is accomplished by a spacecraft maneuver to view the moon when the spacecraft is in the nighttime portion of its orbit.

The eight SeaWiFS spectral bands are as follows:

Band	Wavelength
1	402–422 nm
2	433–453 nm
3	480–500 nm
4	500–520 nm
5	545–565 nm
6	660–680 nm
7	745–785 nm
8	845–885 nm

SeaWiFS Data Products

The NASA SeaWiFS Team has developed, and operates, a data system that processes, calibrates, validates, archives, and distributes SeaWiFS data for research. Prior to December 23, 2004, access to SeaWiFS data was provided to a number of SeaWiFS Authorized Research Users strictly for research and educational use. The data from SeaWiFS, primarily intended for use by marine researchers, provides information that can be used to investigate biological productivity in the ocean, marine optical properties, and the human influence on the oceanic environment.

As of December 23, 2004, the agreement that allowed NASA to acquire SeaWiFS data expired. NASA and ORBIMAGE have been unable to reach a mutually acceptable arrangement that would allow data acquisition to continue beyond that date. Therefore, as of December 23, 2004, any ocean color researchers who wish to continue to use SeaWiFS data must contact ORBIMAGE directly to arrange for continued access to the data. There is a link on the ORBIMAGE website (www.orbimage.com) that provides details for the data access policies and pricing for both commercial and research uses of SeaWiFS (OV-2) data. All current NASA-authorized receiving stations must also contact ORBIMAGE directly to arrange for continued access to decryption keys.

SeaWiFS Data Set Start Date: September 1, 1997

Additional information about the data is available at:
daac.gsfc.nasa.gov/data/dataset/SEAWIFS/.

SORCE

Solar Radiation and Climate Experiment

SORCE URL
lasp.colorado.edu/sorce/

Key SORCE Facts

Spacecraft: Based on Orbital Science's LeoStar 2 Spacecraft

Orbit:
- Type: Non-sun-synchronous
- Equatorial Crossing: N/A
- Altitude: 630 km
- Inclination: 40°
- Period: 97 minutes
- Repeat Cycle: N/A

Dimensions: 339.3 cm × 160.3 cm (deployed)

Mass: 315 kg

Power: 120 W (Orbit average)

Downlink: 1.5 Mbps

Design Life: 5 years

Contributors: LASP-CU, Orbital Sciences Corporation

Summary

SORCE observations are improving our understanding and generating new inquiry regarding how and why solar variability occurs and how it affects our atmosphere and climate. This knowledge is used to estimate past and future solar behavior and climate response.

Instruments

- Spectral Irradiance Monitor (SIM)
- Solar Stellar Irradiance Comparison Experiment (SOLSTICE)
- Total Irradiance Monitor (TIM)
- XUV Photometer System (XPS)

Points of Contact

- *SORCE Principal Investigator:* Tom Woods, Laboratory for Atmospheric and Space Physics/ University of Colorado (Boulder)
- *SORCE Project Scientist:* Robert Cahalan, NASA Goddard Space Flight Center
- *SORCE Deputy Project Scientist:* Doug Rabin, NASA Goddard Space Flight Center

Other Key Personnel

- *SORCE Program Scientist:* Donald Anderson, NASA Headquarters
- *SORCE Program Executive:* Lou Schuster, NASA Headquarters
- *SORCE Program Manager:* Tom Sparn, Laboratory for Atmospheric and Space Physics/University of Colorado (Boulder)

Mission Type

Earth Observing System (EOS) Systematic Measurements

Launch

- *Date and Location:* January 25, 2003, from Kennedy Space Center, Florida
- *Vehicle:* Pegasus XL Rocket

Relevant Science Focus Area

(see NASA's Earth Science Program section)

- Atmospheric Composition
- Climate Variability and Change
- Water and Energy Cycles

Related Applications

(see Applied Sciences Program section)

- Public Health
- Renewable Energy

SORCE Science Goals

SORCE is part of the NASA Earth Observing System of satellites, a series of satellite missions designed to monitor the Earth system from space. These sustained and comprehensive observations include the measurement of solar irradiance as the dominant direct energy input to land, ocean, and atmosphere. As an integral part of this, the SORCE mission aims to:

- Make precise and accurate measurements of the total solar irradiance (TSI). These observations are connected to previous TSI measurements to form a long-term record of solar influences on Earth. SORCE TSI measurements have an absolute accuracy of 0.01% and a long-term relative accuracy of 0.001% (10 ppm) per year.

- Establish a precise data set of solar spectral irradiance (SSI) measurements of the visible and near infrared suitable for future climate studies. These daily SSI measurements are from 200–2000 nm with a spectral resolution ($\Delta\lambda/\lambda$) of < 1/30, an absolute accuracy of 0.03% and a precision and relative accuracy of better than 0.01% per year.

- Make daily measurements of the solar ultraviolet irradiance from 115–320 nm with a spectral resolution of 0.1 nm. This measurement has an absolute accuracy of better than 5% and a long-term relative accuracy of 0.5% per year. The stellar comparisons to a number of bright, early-type stars are used as an in-flight calibration to correct possible changes in the instrument responsivity.

SORCE observations are improving our understanding and generating new inquiry regarding how and why solar variability occurs and how it affects our atmosphere and climate. This knowledge is used to estimate past and future solar behavior and climate response.

SORCE Mission Background

Solar radiation, Earth's average albedo, and long wave infrared emission are key to determining Earth's global average equilibrium temperature. Measurements obtained during the past 25 years show that the total solar irradiance, TSI, varies ~0.1% over the solar cycle, with larger short-term variations. The variations occur over all time scales up to and exceeding the 11-year solar cycle. Climate models including a realistic sensitivity to solar forcing indicate corresponding global surface temperature changes on the order of 0.2° C for recorded solar variations over the last century. However, global energy balance considerations may not provide the entire story. How TSI variations are distributed in wavelength is critically important in understanding Earth's response to solar variations.

Because of selective absorption and scattering processes in the atmosphere, different regions of the solar spectrum affect Earth's climate in distinct ways. Approximately 20–25% of the TSI is absorbed by atmospheric water vapor, clouds, and ozone, influencing convection, cloud formation, and latent heating via processes that are strongly wavelength dependent. Wavelengths below 300 nm are completely absorbed by Earth's atmosphere and contribute the dominant energy source in the stratosphere and thermosphere, establishing the upper atmosphere's temperature structure, composition, and dynamics. The Sun's radiation at these short wavelengths can vary by a factor of two or greater and lead to significant changes in atmospheric chemistry. The solar ultraviolet radiation influences stratospheric chemistry and dynamics, which in turn control the ultraviolet radiation that reaches the surface. Radiation at visible and infrared wavelengths, containing the bulk of the solar energy, penetrates into the lower atmosphere. The non-reflected portion of this radiation is absorbed in the troposphere or at Earth's surface,

SORCE Instruments

SIM
Spectral Irradiance Monitor

SIM incorporates an entirely different technique than previous solar irradiance measurement instruments to obtain the first continuous record of the top of the atmosphere SSI in the visible/near infrared region.

SOLSTICE
Solar Stellar Irradiance Comparison Experiment

The Solar Stellar Irradiance Comparison Experiment (SOLSTICE) instrument measures solar ultraviolet irradiance in the band 115–320 nm. SORCE SOLSTICE is an evolution and refinement of the SOLSTICE on the Upper Atmosphere Research Satellite (UARS), and both the UARS and SORCE SOLSTICE instruments observe the same bright blue stars as long-term calibration standards.

TIM
Total Irradiance Monitor

TIM provides a measurement of TSI with an absolute accuracy of 0.01% and a relative stability of 0.001% per year. Imperative for climate modeling, this instrument reports the average daily value of the Sun's radiative input at the top of Earth's atmosphere.

XPS
XUV Photometer System

XPS measures the solar soft X-ray (XUV) irradiance from 1–34 nm and the bright hydrogen emission at 121.6 nm (Lyman-α). This is an upgraded version of the XPS that extends the solar XUV irradiance measurements with improvements in accuracy, spectral range, and temporal coverage.

becoming a dominant term in the global energy balance and an essential determinant of atmospheric stability and convection. To understand the effects solar variability has on Earth's climate, it is important to monitor both the TSI and its spectral components accurately.

The Sun has both direct and indirect influences on the terrestrial system, and SORCE's comprehensive total and spectral solar measurements are providing the requisite understanding of this important climate system variable.

SORCE carries four instruments to measure the solar radiation incident at the top of Earth's atmosphere. The SORCE mission is a joint effort between NASA and the Laboratory for Atmospheric and Space Physics (LASP) at the University of Colorado. LASP developed, calibrated, and tested the four science instruments and integrated them onto the spacecraft provided by Orbital Sciences Corporation. The SORCE science and mission operations are conducted from LASP's Mission Operations Center.

SORCE Mission and Science Operations

The SORCE satellite is orbiting Earth every 97 minutes, or 15 times daily. Ground stations at Wallops Island, Virginia, and Santiago, Chile, are providing the communication links to the satellite two times each day. The LASP Mission Operations Center (MOC) provides the computer hardware and software necessary to conduct spacecraft operational activities, including command and control of the satellite, mission planning, and assessment and maintenance of spacecraft and instrument health. The science operations include experiment planning, data processing and analysis, validation, and distribution of the finished data product.

Within 48 hours of data capture, all instrument science data and spacecraft engineering data are processed to derive Level 3 science data products in standard geophysical units (W/m^2 or $W/m^2/nm$). The Level 3 data consist of daily and 6-hour average solar irradiances, with higher time resolution data available to meet secondary science objectives, such as studying the passage of bright faculae and dark sunspots across the visible surface of the Sun. All validated data are delivered to the NASA Goddard Space Flight Center Earth Sciences (GES) Distributed Active Archive Center (DAAC) for distribution and long-term storage.

Key SIM Facts

Heritage: New technology developed for SORCE

Instrument Type: Dual Fèry Prism Spectrometer

Scan Type: Solar pointing

Calibration: ESR detector is an absolute detector, and prism transmission calibrations

Field of View (FOV): 1.5° × 3.5°

Instrument IFOV: 1.5° × 3.5°

Transmission Rate: N/A

Swath: N/A

Spatial Resolution: N/A

Spectral Range: 200–2000 nm

Dimensions: 19 cm × 33 cm × 81 cm

Mass: 30.3 kg

Power: 25.3 W

Duty Cycle: 100%

Data Rate: 1001 bps

Contributor: LASP–CU

Key SOLSTICE Facts

Heritage: Upper Atmosphere Research Satellite (UARS) SOLSTICE

Instrument Type: Grating spectrometer

Scan Type: Solar and stellar pointing

Calibration: NIST Synchrotron Ultraviolet Radiation Facility (SURF-III)

FOV: 1.5° × 1.5°

Transmission Rate: N/A

Swath: N/A

Spatial Resolution: N/A

Spectral Range: 115–320 nm

Dimensions: 18 cm × 39 cm × 88 cm

Mass: 21.1 kg

Power: 13 W

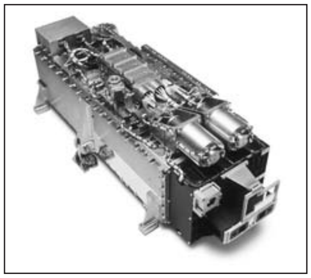
Duty Cycle: 100%

Data Rate: 521 bps

Contributor: LASP–CU

SIM

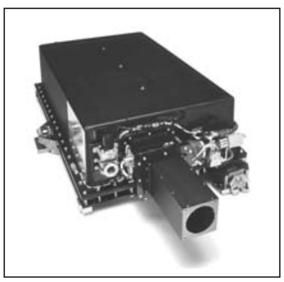
Spectral Irradiance Monitor



The newly developed SIM instrument incorporates an entirely different technique to make the first continuous record of the top of the atmosphere SSI in the visible/near infrared region. It uses a prism as the self-calibrating, single optical element and a miniature absolute ESR as the primary detector. This instrument provides spectral measurements over the range 200–2000 nm. Solar variability models, with the additional constraint of TSI observations, predict very small fractional changes—only 0.01–0.1% —in the visible/near infrared irradiance spectrum. Understanding the wavelength-dependent solar variability is of primary importance for determining long-term climate change processes.

SOLSTICE

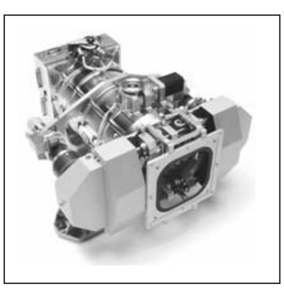
Solar Stellar Irradiance Comparison Experiment



There are two identical SOLSTICE instruments that measure solar ultraviolet irradiance over the range 115–320 nm. These instruments are an evolution and refinement of the Upper Atmosphere Research Satellite's (UARS) SOLSTICE, and they observe the same bright blue stars as long-term calibration standards. These stellar targets establish corrections to the instrument sensitivity, since these stars remain extremely constant. Previous solar measurements show that far ultraviolet irradiance varies by as much as 10% during the Sun's 27-day rotation, while the bright 121.6 nm hydrogen Lyman-α emission may vary by as much as a factor of two during an 11-year solar cycle, dramatically affecting the energy input into the Earth's upper atmosphere.

TIM

Total Irradiance Monitor



TIM uses the best heritage of previous electrical substitution radiometers (ESRs), but is enhanced with state-of-the-art technologies including phase-sensitive detection, metallic absorptive materials, and digital electronics. The TIM provides a measurement of TSI with an absolute accuracy of 0.01%

Key TIM Facts

Heritage: The TIM is a new instrument to continue the TSI measurements of ACRIM, VIRGO, and ERBS.

Instrument Type: Electrical Substitution Radiometer (ESR)

Scan Type: Solar pointing

Calibration: Absolute detector, characterized at LASP, University of Colorado

FOV: 12.8°

Transmission Rate: N/A

Swath: N/A

Spatial Resolution: N/A

Spectral Range: Integrated solar spectrum

Dimensions: 20 cm × 30 cm × 34 cm

Mass: 10.7 kg

Power: 14 W

Duty Cycle: 100%

Data Rate: 713 bps

Contributor: LASP–CU

Key XPS Facts

Heritage: Student Nitric Oxide Explorer (SNOE) Solar XUV Photometers (SXP), Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) Solar EUV Experiment (SEE)

Instrument Type: Set of 12 spectrophotometers

Scan Type: N/A

Calibration: NIST Synchrotron Ultraviolet Radiation Facility (SURF-III)

FOV: 4°

Transmission Rate: N/A

Swath: N/A

Spatial Resolution: N/A

Spectral Range: 1–34 nm and 121–122 nm

Dimensions: 16 cm × 22 cm × 17 cm

Mass: 4.5 kg

Power: 9 W

Duty Cycle: 70%

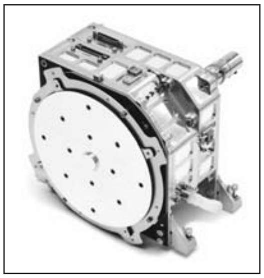
Data Rate: 204 bps

Contributor: LASP–CU

and a relative stability of 0.001% per year. Imperative for climate modeling, this instrument reports the total daily value of the Sun's radiative input at the top of the Earth's atmosphere. .

XPS

XUV Photometer System



The XPS instrument measures the solar soft X-ray (XUV) irradiance from 1–34 nm and the bright hydrogen emission at 121.6 nm (Lyman-α). The solar XUV radiation is emitted from the hot, highly-variable corona on the Sun, and these high-energy photons are a primary energy source for heating and ionizing Earth's upper atmosphere. The XPS is also sensitive to solar flare events, during which the solar XUV radiation can change by a factor of 2–10. The SORCE XPS, which evolved from earlier versions flown on SNOE and TIMED, extends the solar XUV irradiance measurements with improvements in accuracy, spectral range, and temporal coverage.

SORCE References

Drake, V. A., W. McClintock, R. Kohnert, T. Woods, and G. Rottman, 2000: Photomultiplier tube detector performance and stability for the Earth Observing System's SOLSTICE II instrument. *SPIE Proceedings*, **4139**, 402–411.

Fontenla, J., J. Harder, G. Rottman, T. N. Woods, G. M. Lawrence, and S. Davis, 2004: The signature of solar activity in the infrared spectral irradiance. *Astrophysical J. Lett.*, **605**, L85–L88.

Harder, J., G. Lawrence, G. Rottman, and T. Woods, 2000: The Spectral Irradiance Monitor (SIM) for the SORCE mission. *SPIE Proceedings*, **4135**, 204–214.

Harder, J., G. Lawrence, G. Rottman, and T. Woods, 2000: The Solar Spectral Irradiance Monitor: SIM. *Metrologia*, **37**, 415–418.

Kopp, G., G. Lawrence, and G. Rottman, 2003: Total Irradiance Monitor design and on-orbit functionality. *SPIE Proceedings*, 5171–5174.

Lawrence, G. M., G. Kopp, G. Rottman, J. Harder, T. Woods, and H. Loui, 2003: Calibration of the Total Irradiance Monitor. *Metrologia*, **40**, S78–S80.

Lawrence, G. M., G. Rottman. G. Kopp, J. Harder, W. McClintock, and T. Woods, 2000: The Total Irradiance Monitor (TIM) for the EOS SORCE mission. *SPIE Proceedings*, **4135**, 215–224.

Lawrence, G. M., G. Rottman, J. Harder, and T. Woods, 2000: Solar Total Irradiance Monitor: TIM. *Metrologia*, **37**, 407–410.

Lawrence, G. M., J. Harder, G. Rottman, T. Woods, J. Richardson, and G. Mount, 1998: Stability considerations for a solar Spectral Intensity Monitor (SIM). *SPIE Proceedings*, **3427**, 477–485.

McClintock, W. E., G. J. Rottman, and T. N. Woods, 2000: SOLar Stellar Irradiance Comparison Experiment II (SOLSTICE II) for the NASA Earth Observing System's Solar Radiation and Climate Experiment mission. *SPIE Proceedings*, **4135**, 225–234.

Rottman, G., 2000: Solar UV irradiance measurements: the UARS and EOS SOLSTICE. *Physics and Chemistry of the Earth, Part C: Solar-Terrestrial and Planetary Science*, **25**, 401–404.

Rottman, G. J., T. N. Woods, and W. McClintock, 2006: SORCE solar UV irradiance results. *Adv. Space Res.*, **37**, 201–208.

Rottman, G. J., G. Mount, G. Lawrence, T. Woods, J. Harder, and S. Tournois, 1998: Solar spectral irradiance measurements: Visible to near infrared, NEWRAD'97. *Metrologia*, **35**, 707–712.

Woods, T. N., and G. J. Rottman, 2001: Solar ultraviolet variability over time periods of aeronomic interest: 2001. In M. Mendillo, A. Nagy, and J. Hunter Waite, Jr., eds., *Comparative Aeronomy in the Solar System*, AGU Monograph Series, Washington, DC.

Woods, T. N., F. G. Eparvier, J. Fontenla, J. Harder, G. Kopp, W. E. McClintock, G. Rottman, B. Smiley, and M. Snow, 2004: Solar irradiance variability during the October 2003 solar storm period. *Geophys. Res. Lett.*, **31**, L10802.

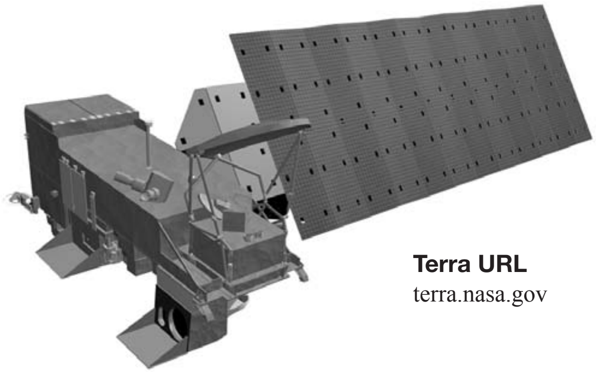
Woods, T., G. Rottman, J. Harder, G. Lawrence, B. McClintock, G. Kopp, and C. Pankratz, 2000: Overview of the EOS SORCE mission. *SPIE Proceedings*, **4135**, 192–203.

SORCE Data Products

Product Name or Grouping	Processing Level	Coverage	Spatial/Temporal Characteristics
TIM *Data Set Start Date: February 25, 2003*			
Total Solar Irradiance (TSI)	3	Measured at the top of the atmosphere	4 times daily
SIM, SOLSTICE, XPS *Data Set Start Date: March 5, 2003*			
Spectral Solar Irradiance (1–2000 nm)	3	Measured at the top of the atmosphere	4 times daily

SORCE Data Products

Terra



Terra URL
terra.nasa.gov

Key Terra Facts

Joint with Japan and Canada

Orbit:
Type: Near-polar, sun-synchronous
Equatorial Crossing: 10:30 a.m.
Altitude: 705 km
Inclination: 98.1°
Period: 98.88 minutes
Repeat Cycle: 16 days

Dimensions: 2.7 m × 3.3 m × 6.8 m

Mass: 5,190 kg

Power: 2,530 W

Design Life: 6 years

Summary

The Terra (formerly called EOS AM-1) satellite is the flagship of NASA's Earth Science Missions. Terra is the first EOS (Earth Observing System) platform and provides global data on the state of the atmosphere, land, and oceans, as well as their interactions with solar radiation and with one another.

Instruments

- Clouds and the Earth's Radiant Energy System (CERES; two copies)
- Multi-angle Imaging SpectroRadiometer (MISR)
- Moderate Resolution Imaging Spectroradiometer (MODIS)
- Measurements of Pollution in The Troposphere (MOPITT)
- Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)

Points of Contact

- *Terra Project Scientist:* Marc Imhoff, NASA Goddard Space Flight Center
- *Terra Deputy Project Scientist:* Si-Chee Tsay, NASA Goddard Space Flight Center

Other Key Personnel

- *Terra Program Scientist:* Garik Gutman, NASA Headquarters
- *Terra Program Executive:* Lou Schuster, NASA Headquarters

Mission Type

Earth Observing System (EOS) Systematic Measurements

Launch

- *Date and Location:* December 18, 1999, from Vandenberg Air Force Base, California
- *Vehicle:* Atlas Centaur IIAS expendable launch vehicle

Relevant Science Focus Areas

(see NASA's Earth Science Program section)

- Atmospheric Composition
- Carbon Cycle, Ecosystems, and Biogeochemistry
- Climate Variability and Change
- Earth Surface and Interior
- Water and Energy Cycles
- Weather

Related Applications

(see Applied Science Program section)

- Agricultural Efficiency
- Air Quality
- Carbon Management
- Coastal Management
- Disaster Management
- Ecological Forecasting
- Energy Management
- Homeland Security
- Invasive Species
- Public Health
- Water Management

Terra Science Goals

- Provide the first global and seasonal measurements of the Earth system, including such critical functions as biological productivity of the land and oceans, snow and ice, surface temperature, clouds, water vapor, and land cover.

- Improve our ability to detect human impacts on the Earth system and climate, identify the 'fingerprint' of human activity on climate, and predict climate change by using the new global observations in climate models.

- Help develop technologies for disaster prediction, characterization, and risk reduction from wildfires, volcanoes, floods, and droughts.

- Start long-term monitoring of global climate change and environmental change.

Terra Mission Background

The Terra mission provides comprehensive global measurements for quantitatively monitoring Earth's land, oceans, and atmosphere. Terra, along with other EOS spacecraft (Landsat 7, Aqua, and ICESat) acquires many of the measurements required to advance understanding of the Earth system. Terra flies in a near-polar, sun-synchronous orbit that descends across the equator in the morning. After launch in December 1999, Terra's equator crossing time was changed from around 10:45 a.m. local time to 10:30 a.m. ± 5 minutes after a series of inclination maneuvers. This crossing time is expected to be maintained for the rest of the mission.

Terra's orbit follows the Worldwide Reference System, as do the orbits of Landsat 7 (USGS), Earth Observing-1 (EO-1, NASA), and Satelite de Aplicaciones Cientificas-C (SAC-C, Argentina Comisión Nacional para el Ahorro de Energia [CONAE]), all crossing the equator within 30 minutes of each other. These four spacecraft compose the 'Morning Constellation,' thus facilitating joint use of Terra data and the data from its companion missions. The Aqua spacecraft, launched in May 2002, flies in an ascending orbit with a 1:30 p.m. equatorial crossing time, which enables study of diurnal variability with the MODIS and CERES instruments on both Terra and Aqua. For additional information about the Terra spacecraft and links to each of its five instruments, the reader is invited to visit the Terra Project Science homepage at: terra.nasa.gov.

Each Terra instrument was developed under the supervision of a science team that also provides algorithms for analysis of the data and derivation of Earth-system measurements. The science teams validate these products and use them in scientific investigations. Terra has five complementary scientific instruments: ASTER for close-up land studies, CERES for a broad view of long- and shortwave radiation, MOPITT for studies of pollution, MISR for bidirectional-reflectance studies of clouds, aerosol, and land features, and MODIS for global analysis of land, ocean, and atmosphere properties and their interactions. The MODIS and CERES

Terra Instruments

ASTER
Advanced Spaceborne Thermal Emission and Reflection Radiometer

A 3-radiometer sensor package with three vis/near-IR, six shortwave, and 5 thermal-infrared channels with 15, 30, and 90-m resolution, respectively, and a 60-km swath. Provided by the Japanese Ministry of Economy, Trade, and Industry (METI), designed to make detailed maps of land surface temperature, emissivity, reflectance and elevation.

CERES
Clouds and the Earth's Radiant Energy System

A 3-channel, broadband radiometer (0.3 to > 100 μm, 0.3–5 μm, 8–12 μm) designed to measure major elements of the Earth's radiation balance.

MISR
Multi-angle Imaging SpectroRadiometer

A 36-channel instrument; nine push-broom cameras with discrete view angles (to ±70°) in four spectral bands (0.443–0.865 m) with resolutions of 275 m to 1.1 km, designed to measure clouds, aerosols and vegetation cover.

MODIS
Moderate Resolution Imaging Spectroradiometer

A 36-band spectroradiometer measuring visible and infrared radiation (0.4–14.5 μm with spatial resolutions of 250 m, 500 m, and 1 km at nadir) for derivation of products ranging from land vegetation and ocean chlorophyll fluorescence to cloud and aerosol properties, fire occurrence, snow cover on land, and sea ice in the oceans.

MOPITT
Measurements of Pollution in The Troposphere

An 8-channel cross-track-scanning gas-correlation radiometer operating at three wavelengths (2.2, 2.3, and 4.7 μm), designed to measure carbon monoxide and methane in the atmosphere.

instruments extend the measurements of their heritage sensors—the Advanced Very High Resolution Radiometer (AVHRR), the Coastal Zone Color Scanner (CZCS), and the Earth Radiation Budget Experiment (ERBE)—but with a higher quality of calibration and characterization.

Over the course of the mission, Terra's MODIS and MOPITT instruments have experienced some anomalies. The MODIS instrument power supply and scientific formatting equipment experienced problems in 2001 and 2002, respectively, and were switched to redundant units. MOPITT experienced the loss of four of its channels in 2001, resulting in a reduction of carbon monoxide profiling capability. Despite these problems MOPITT is acquiring science data for both carbon monoxide and methane. ASTER, MISR, and CERES have operated throughout the mission with no significant problems.

The amount of downloaded data from Terra's instruments is about 195 Gb of Level 0 data each day, which represents about 850 terabytes when processed to higher-level science products. Currently, the majority of planned Terra science products are available through the EOS Data Gateway. At this point in the mission, most products are calibrated and validated and have been given the label of 'validated' data. This means that a data product has been evaluated and quality checked and is considered ready for routine scientific research uses. Nonetheless, validation research is continuing throughout the lifetime of the Terra mission, and it is reasonable to expect that Terra data products will continue to be improved over time. For the latest information on the status and availability of data from Terra (and similarly for other EOS missions), see: eosdatainfo.gsfc.nasa.gov/terra.

Early in the Terra mission, instrument-team scientists called for a series of on-orbit pitch-over maneuvers to allow Terra's instruments to view cold deep space or the sunlit lunar surface. Data from the deep-space maneuvers were required to enable CERES to confirm offsets for its longwave-radiation measurements and enable MODIS to adequately characterize response as a function of mirror scan angle. ASTER, MISR, and MODIS science teams desired measurements of the lunar surface for radiometric calibration purposes. The maneuver required a reverse pitch during eclipse (spacecraft night) within about 33 minutes.

The first Terra deep-space calibration maneuver was successfully performed on March 26, 2003, followed by an identical and flawless maneuver with the moon in the viewing plane of the instruments on April 14, 2003. NASA's EO-1 Advanced Land Imager (ALI) and Hyperion instruments and OrbView's Sea-Viewing Wide Field-of-view Sensor (SeaWiFS) acquired data of the moon around the time of Terra's maneuver. Intercomparisons with these instruments are planned. Analysis of the measurements from the deep space and lunar maneuvers are currently underway, and final results may lead to a plan for a third maneuver.

Through satellite and other observations, the scientific community now has unprecedented quantitative data sets to study Earth as a system and answer the questions of how is Earth changing and how will humans be affected by these changes. Terra, as the flagship observatory for NASA's Earth Observing System, is contributing valuable new data, leading to new insights about the Earth system.

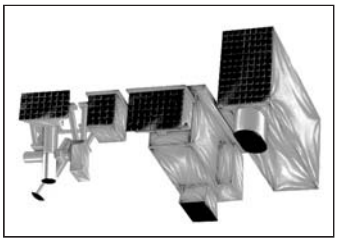
Terra Partners

The Terra Project Office, located at NASA GSFC, manages Terra development. GSFC was responsible for the development of the satellite and the development and operation of the ground operations system. Spacecraft operations are performed at a Mission Operations Center at GSFC.

ASTER

Advanced Spaceborne Thermal Emission and Reflection Radiometer

ASTER Background



ASTER is a facility instrument provided for the Terra platform by Japan's Ministry of Economy, Trade and Industry (METI). It provides high-spatial-resolution (15- to 90-m) multispectral images of Earth's surface and clouds in order to better understand the physical processes that affect climate change. While MODIS and MISR monitor many of the same variables globally, and on a daily basis, ASTER provides data at a scale that can be directly related to detailed physical processes. These data bridge the gap between field observations and data acquired by MODIS and MISR, and between process models and climate and/or forecast models. ASTER data are also used for long-term monitoring of local and regional changes on Earth's surface, which either lead to, or are in response to, global climate change, e.g., land use, deforestation, desertification, lake and playa water-level changes, and other changes in vegetation communities, glacial movement, and volcanic processes.

Clouds are one of the most important variables in the global climate system. With its high spatial resolution, broad spectral coverage, and stereo capability, ASTER provides essential measurements of cloud amount, type, spatial distribution, morphology, and radiative properties.

ASTER provides radiative (brightness) temperature, and the multispectral thermal infrared (TIR) data can be used to derive surface kinetic temperature and spectral emissivity. Radiative temperature is an element in the surface heat balance. Surface kinetic temperature can be used to determine elements of surface-process models, sensible heat flux, latent heat flux, and ground heat conduction. Surface temperatures are also related to thermophysical properties (such as thermal inertia), vegetation health, soil moisture, temporal land classification, e.g., wet vs. dry, vegetated vs. bare soil, and evapotranspiration.

ASTER operates in three visible and near-infrared (VNIR) channels between 0.5 and 0.9 µm, with 15-m resolution; six short-wave infrared (SWIR) channels between 1.6 and 2.43 µm, with 30-m resolution; and five TIR channels between 8 and 12 µm, with 90-m resolution. The instrument acquires data over a 60-km swath whose center is pointable cross-track ±8.55° in the SWIR and TIR, with the VNIR pointable out to ±24°. An additional VNIR telescope (aft pointing) covers the wavelength range of Channel 3. By combining these data with those for Channel 3, stereo views can be created, with a base-to-height ratio of 0.6. ASTER's pointing capabilities are such that any point on the globe is accessible at least once every 16 days in all 14 bands and, on average, every 4 days in the three VNIR channels.

ASTER data products exploit combinations of VNIR, SWIR, and TIR for cloud studies, surface mapping, soil and geologic

Key ASTER Facts

Japan provided the instrument, which provides high-resolution images of the land surface, water, ice, and clouds and has same-orbit stereo capability.

Heritage: Japanese Earth Resources Satellite-1 (JERS-1), Optical Sensor (OPS), and Landsat

Instrument Type: Multispectral imaging radiometer for reflected and emitted radiation measurements of the Earth's surface

Absolute Radiometric Accuracy: 4% in VNIR and SWIR bands

Absolute Temperature Accuracy: 3 K in 200–240 K range, 2 K in 240–270 K range, 1 K in 270–340 K range, and 2 K in 340–370 K range for TIR bands

Swath: 60 km at nadir; swath center is pointable cross-track, ±106 km for SWIR and TIR, and ± 314 km for VNIR

Spatial Resolution: VNIR (0.5–0.9 µm), 15 m [stereo (0.7–0.9 µm), 15 m horizontal, 25 m vertical]; SWIR (1.6–2.43 µm), 30 m; TIR (8–12 µm), 90 m

Dimensions:

- VNIR: 57.9 cm × 65.1 cm × 83.2 cm
- SWIR: 72.3 cm × 134 cm × 90.6 cm
- TIR: 73 cm × 183 cm × 110 cm
- Common Signal Processor (CSP)/VEL (electronics): 33.4 cm × 54 cm × 31.5 cm
- Master Power Supply (electronics): 30 cm × 50 cm × 32 cm

Mass: 421 kg

Duty Cycle: 8% (VNIR and SWIR, daylight only), 16% (TIR)

Power: 463 W (average), 646 W (peak)

Data Rate: 8.3 Mbps (average), 89.2 Mbps (peak)

Thermal Control: 80 K Stirling-cycle coolers, heaters, cold-plate/capillary-pumped loop, and radiators

Thermal Operating Range: 10–28° C

Field of View (FOV) (all pointing is near nadir, except VNIR has both nadir and 27.6° backward from nadir): VNIR: 6.09° (nadir), 5.19° (backward), SWIR and TIR: 4.9°

Instrument IFOV: VNIR: 21.5 µrad (nadir), 18.6 µrad (backward), SWIR: 42.6 µrad (nadir), TIR: 128 µrad (nadir) studies, volcano monitoring, and surface temperature, emissivity, and reflectivity determination. VNIR and SWIR bands are used for investigation of land-use patterns and vegetation, VNIR and TIR combinations for the study of coral reefs and glaciers, and VNIR for digital elevation models (DEMs). TIR channels are used for study of evapotranspiration and land and ocean temperature. The stereoscopic capability yields local surface DEMs and allows observations of local topography, cloud structure, volcanic plumes, and glacial changes.

ASTER URL

asterweb.jpl.nasa.gov

Japan ASTER Science Team Leader

Hiroji Tsu, Geological Society of Japan

U.S. ASTER Science Team Leader

Michael Abrams, NASA Jet Propulsion Laboratory/California Institute of Technology

Key ASTER Facts *(cont.)*

Spectral Range: 14 multispectral bands from visible through thermal infrared

Direct Readout: No

Prime Contractor: NEC (systems integration, VNIR, and Common Signal Processor)

Subcontractors: MELCO (SWIR and cryocooler), Fujitsu (TIR and cryocooler), and Hitachi (master power supply)

CERES

Clouds and the Earth's Radiant Energy System

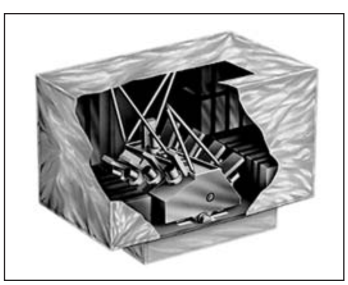
The CERES instrument is described in the Aqua section.

MISR

Multi-angle Imaging SpectroRadiometer

Provides top-of-atmosphere bidirectional reflectances and albedos, cloud-top heights and cloud-tracked winds, cloud classifiers and masks, aerosol optical depths and particle properties, surface bidirectional reflectances, albedos, leaf-area index, and fractional absorbed photosynthetically active radiation.

MISR Background



MISR routinely provides multiple-angle, continuous-sunlight coverage of Earth with moderately high spatial resolution. The instrument obtains multidirectional observations of each scene within a time scale of minutes, thereby under almost identical atmospheric conditions. MISR uses nine individual CCD-based pushbroom cameras to observe Earth at nine discrete view angles: one at nadir, plus eight other symmetrical views at 26.1°, 45.6°, 60.0°, and 70.5°

Key MISR Facts

Built by the NASA Jet Propulsion Laboratory

Heritage: Galileo, Wide-Field/Planetary Camera

Instruments: Nine charge-coupled device (CCD) cameras fixed at nine viewing angles out to 70.5° at the Earth's surface, forward and afterward of nadir, including nadir

Spectral Bands: Four spectral bands discriminated via filters bonded to the CCDs

Swath: 380 km viewed in common by all nine cameras

Spatial Sampling: 275 m, 550 m, or 1.1 km, selectable in-flight

Repeat Cycle: Global coverage in 9 days

Dimensions: 0.9 m × 0.9 m × 1.3 m

Mass: 149 kg

Duty Cycle: 50%

Power: 83 W (average), 131 W (peak)

Thermal Control: Passive cooling and active temperature stabilization

Thermal Operating Range: 0–10° C

FOV: ±60° (along-track) × ±15° (cross-track)

Data Rate: 3.3 Mbps (orbit average), 9.0 Mbps (peak)

Direct Broadcast: No

forward and aftward of nadir. Images at each angle are obtained in four spectral bands centered at 446, 558, 672, and 866 nm. Each of the 36 instrument data channels (4 spectral bands × 9 cameras) is individually commandable to provide ground sampling of 275 m, 550 m, or 1.1 km. The common swath width of all 9 MISR cameras is about 380 km, providing global multi-angle coverage of the entire Earth in nine days at the equator, and 2 days at the poles. The instrument design and calibration strategies maintain absolute radiometric uncertainty to ±4%. This is met through the bimonthly use of an onboard calibrator and annual field calibration exercises that make use of surface measurements and data from the MISR airborne simulator, AirMISR.

MISR images are acquired in two observing modes: Global and Local. Global Mode provides continuous planet-wide observations, with all of the nadir channels and the red band of all of the off-nadir cameras operating at 275-m resolution and everything else operating at 1.1-km resolution. Local Mode provides data at 275-m resolution in all spectral bands and all cameras for selected 380-km × 300-km regions. In addition to data products providing radiometrically calibrated and geo-rectified images, Global Mode data are used to generate the standard Level 2 Top-of-Atmosphere (TOA)/Cloud Products and Aerosol and Surface Products. Level 3 monthly, seasonal, and annual summary products are generated from Level 1 and Level 2 inputs.

The purpose of the TOA/Cloud Product suite is to enable study, on a global basis, of the use of remotely sensed radiances for inferring cloud properties and albedos, taking into account the effects of cloud-field heterogeneity, altitude, and three-dimensional morphology on the solar radiance and irradiance reflected to space. These products also provide angular signature and stereoscopic cloud identifiers that are particularly useful over challenging areas such as snow- and ice-covered surfaces. The aerosol parameters contained within the Aerosol and Surface Products enable study, on a global basis, of the magnitude and natural variability in space and time of sunlight absorption and scattering by different aerosol types over many kinds of surfaces, including bright-desert source regions. These products also provide atmospheric correction inputs for surface-imaging data acquired by MISR and other instruments that are simultaneously viewing the same portion of the Earth. The surface parameters within the Aerosol and Surface Product are designed to enable improved measures of land-surface characteristics, using bidirectional and hemispherical reflectances to distinguish surface texture and to take into account canopy structure in retrieving global leaf-area index and fractional absorbed photosynthetically active radiation.

MISR URL

www-misr.jpl.nasa.gov/

MISR Principal Investigator

David J. Diner, NASA Jet Propulsion Laboratory/ California Institute of Technology

MODIS

Moderate Resolution Imaging Spectroradiometer

The MODIS instrument is described in the Aqua section.

MOPITT

Measurements of Pollution in The Troposphere

Uses pressure modulation and length modulation to obtain carbon monoxide (CO) concentrations with three independent pieces of information represented by values on seven pressure levels, as well as CO and methane (CH_4) columns.

MOPITT Background

The MOPITT experiment is provided under a Memorandum of Understanding with the Canadian Space Agency (CSA). MOPITT measures emitted and reflected infrared radiance in the atmospheric column which, when analyzed, permits retrieval of tropospheric CO profiles and total column amounts of CO and CH_4.

Both CO and CH_4 are produced by biomass systems, oceans, and human activities. CO is intimately connected with the hydroxyl radical (OH) chemical cycle in the troposphere and moves both vertically and horizontally within the troposphere. CH_4 is a greenhouse gas and is increasing on an annual basis. MOPITT measurements allow studies of the global and temporal distributions that drive energy budget and source/sink studies. Since human activities have a significant influence on both CO and CH_4 concentrations, a better understanding of the role of these constituents is essential to understanding anthropogenic effects on the environment.

MOPITT operates on the principle of correlation spectroscopy, i.e., spectral selection of radiation emission or absorption by a gas, using a sample of the same gas as a filter. The instrument modulates sample-gas density by changing the length or the pressure of the gas sample in the optical path of the instrument. This modulation changes the absorption profile in the spectral lines of the gas in the cell as observed by a detector. The modulated-gas sample acts as an optical filter, which selectively picks out the parts of the atmospheric absorption lines of that gas in the atmosphere. The detector thus observes a signal highly correlated with the abundance of the sample gas in the atmosphere.

Atmospheric sounding and column CO are mapped by using thermal and reflected solar channels in the regions of 4.7 and 2.3 µm, respectively. Column CO and CH_4 are measured using solar channels viewed through modulation cells to sense solar radiation reflected from the surface. The solar channels are duplicated in the instrument at different correlation-cell pressures, to allow a failure in one channel without compromising the column measurement.

MOPITT is designed as a scanning instrument. The field of 4 pixels, aligned along the direction of motion, and each 1.8° (or 22 km at nadir) on a side, is scanned through a cross-track scan angle of 26.1°, or 29 pixels, to give a swath width of 640 km. This swath leaves gaps in coverage between successive orbits using the nominal 705-km altitude and 98.2° inclination orbit.

MOPITT was launched on the Terra spacecraft on December 18, 1999, and was activated in March 2000. Performance to May 2001 was excellent, at which point a problem with the detector cooling system degraded the instrument performance somewhat. However, data are still being obtained by the instrument, and studies have shown that the performance has only been slightly degraded throughout most of the measurement region. MOPITT data for CO have been taken and processed regularly for the entire mission.

The data products include CO soundings, which are retrieved with 10% accuracy provided by up to three independent pieces of information and are represented by values on seven pressure levels between 0 and 14 km. These soundings are taken at laterally scanned sampled locations with 22-km horizontal resolution.

MOPITT CO data for the first 5 years of the MOPITT mission (March 2000 through May 2005) have been released as validated. Problems were discovered with some ancillary data beginning in June 2005, and as of early 2006 the data from June 2005 onward are being reprocessed with an updated algorithm.

MOPITT URLs

University of Toronto
www.atmosp.physics.utoronto.ca/MOPITT/home.html

National Center for Atmospheric Research
www.eos.ucar.edu/mopitt/

MOPITT Principal Investigator

James Drummond, University of Toronto, Canada

Key MOPITT Facts

Joint with Canada

Heritage: Measurement of Air Pollution from Satellites (MAPS), Pressure Modulator Radiometer (PMR), Stratospheric and Mesospheric Sounder (SAMS), and Improved Stratospheric and Mesospheric Sounder (ISAMS) instruments

Instrument Type: Eight-channel radiometer

CO Concentration Accuracy: 10%

CH_4 Column Abundance Accuracy: 1%

Swath: 640 km (29 fields of view)

Spatial Resolution (each pixel): 22 km × 22 km (at nadir)

Dimensions: 115 cm × 93 cm × 57 cm (stowed), 115 cm × 105 cm × 71 cm (deployed)

Mass: 192 kg

Power: 250 W (average), 260 W (peak)

Duty Cycle: 100%

Data Rate: 28 kbps

Thermal Control: 80 K Stirling-cycle cooler, capillary-pumped cold plate and passive radiation

Thermal Operating Range: 25° C (instrument), 100 K (detectors)

Instrument IFOV: 22 km across track, 88 km along track (1.8° × 7.2° × 4° pixels)

Spectral Range: Correlation spectroscopy utilizing both pressure- and length-modulated gas cells, with detectors at 2.3, 2.4, and 4.7 µm

Direct Broadcast: No; Rapid Response processing available

Prime Contractor: COM DEV

The Canadian Space Agency provided the instrument

Terra References

ASTER References

Fujisada, H., and A. Ono, 1991: Overview of ASTER design concept. *Proc. SPIE*, 1490.

Fujisada, H., and A. Ono, 1992: Observational performance of ASTER instrument on EOS AM-1 spacecraft, in A. B. Kahle, E. J. Njoku, F. D. Palluconi, A. R. Gillespie, S. J. Hook, C. M. Hayden, K. Tsuchiya, and J. Dozier, eds., *Advances in Remote Sensing of Earth's Surface and Atmosphere*, Pergamon Press, New York, 147–150.

Toutin, T., 2002: Three-dimensional topographic mapping with ASTER stereo data in rugged topography. *IEEE Trans. Geosci. Remote Sens.*, **40 (10)**, 2241–2247.

Yamaguchi, Y., A. B. Kahle, H. Tsu, T. Kawakami, and M. Pniel, 1998: Overview of Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER). *IEEE Trans. Geosci. Remote Sens.*, **36**, 1062–1071.

Zhu, G., and D. G. Blumberg, 2002: Classification using ASTER data and SVM algorithms–the case study of Beer Sheva, Israel. *Rem. Sens. Environ.*, **80 (2)**, 233–240.

MISR References

Diner, D. J., J. C. Beckert, T. H. Reilly, C. J. Bruegge, J. E. Conel, R. Kahn, J. V. Martonchik, T. P. Ackerman, R. Davies, S. A. W. Gerstl, H. R. Gordon, J-P. Muller, R. Myneni, P. J. Sellers, B. Pinty, and M. M. Verstraete, 1998: Multi-angle Imaging SpectroRadiometer (MISR) description and experiment overview. *IEEE Trans. Geosci. Remote Sens.*, **36**, 1072–1087.

Diner, D. J., J. C. Beckert, G. W. Bothwell, and J. I. Rodriguez, 2002: Performance of the MISR instrument during its first 20 months in Earth orbit. *IEEE Trans. Geosci. Remote Sens.*, **40**, 1449–1466.

Also see the collection of 17 MISR-related papers in the Special Section on MISR, 2002: *IEEE Trans. Geosci. Remote Sens.*, **40**.

MOPITT References

Bremer, H., J. Kar, J. R. Drummond, F. Nichitiu, J. Zou, J. Liu, J. C. Gille, M. N. Deeter, G. Francis, D. Ziskin, and J. Warner, 2004: Spatial and temporal variation of MOPITT CO in Africa and South America: A comparison with SHADOZ ozone and MODIS aerosol. *J. Geophys. Res.*, **109**, D12304, doi:10.1029/2003JD004234.

Drummond, J. R., 1992: Measurements of Pollution in the Troposphere (MOPITT), in J. Gille and G. Visconti, eds., *The Use of EOS for Studies of Atmospheric Physics*, North Holland, Amsterdam, 77–101.

Drummond, J. R., and G. S. Mand, 1996: The Measurements of Pollution in The Troposphere (MOPITT) instrument: Overall performance and calibration requirements. *J. Atmos. Ocean. Tech.*, **13**, 314–320.

Kar J., H. Bremer, J. R. Drummond, Y. J. Rochon, D. B. A. Jones, F. Nichitiu, J. Zou, J. Liu, J. C. Gille, D. P. Edwards, M. N. Deeter, G. Francis, D. Ziskin, and J. Warner, 2004: Evidence of vertical transport of carbon monoxide from Measurement of Pollution in The Troposphere (MOPITT). *Geophys. Res. Lett.*, **31**, L23105, doi:10.1029/2004G021128.

Lamarque, J.-F., D. P. Edwards, L. K. Emmons, J. C. Gille, O. Wilhelmi, C. Gerbig, D. Prevedel, M. N. Deeter, J. Warner, D. C. Ziskin, B. Khattatov, G. L. Francis, V. Yudin, S. Ho, D. Mao, J. Chen, and J. R. Drummond, 2003: Identification of CO plumes from MOPITT data: Application to the August 2000 Idaho-Montana forest fires. *Geophys. Res. Lett.*, **30 (13)**, 1688, doi:10.1029/2003GL017503.

Liu, J., J. R. Drummond, Q. Li, J. C. Gille, and D. C. Ziskin, 2005: Satellite mapping of CO emission from forest fires in northwest America using MOPITT measurements. *Rem. Sens. Environ.*, **95**, 502–516.

Pan, L., D. Edwards, J. C. Gille, M. W. Smith, and J. R. Drummond, 1995: Satellite remote sensing of tropospheric CO and CH_4. *Appl. Opt.*, **34**, 6976.

Pan, L., J. C. Gille, D. P. Edwards, P. L. Bailey, and C. D. Rodgers, 1998: Retrieval of tropospheric carbon monoxide for the MOPITT experiment. *J. Geophys. Res.*, **103**, 32,277–32,290.

Wang, J., J. Gille, P. L. Bailey, J. R. Drummond, and L. Pan, 1999: Instrument sensitivity and error analysis for the remote sensing of tropospheric carbon monoxide by MOPITT. *J. Atmos. Ocean. Tech.*, **16**, 465–474.

See CERES and MODIS references in the Aqua section.

Terra Data Products

For more information about the data products please see the *EOS Data Products Handbook*, Volume 1 (revised January 2004) available at: eos.nasa.gov/eos_homepage/for_scientists/data_products/. Future updates regarding data products and data availability should be available through the URLs provided in the instrument sections.

Product Name or Grouping	Processing Level	Coverage	Spatial/Temporal Characteristics
ASTER *Data Set Start Date: March 8, 2000*			
Reconstructed, Unprocessed Instrument Data	1A	Regional up to 780 60 km × 60 km scenes per day (daytime for all channels, daytime and nighttime TIR channels, nighttime SWIR and TIR channels for volcano observation)	15 m (VNIR), 30 m (SWIR), 90 m (TIR)
Registered Radiance at Sensor	1B	Regional up to 310 60 km × 60 km scenes per day (daytime and nighttime)	15 m (VNIR), 30 m (SWIR), 90 m (TIR)
Brightness Temperature at Sensor	2	Regional up to 70 64 km × 60 km scenes per day (daytime and nighttime)	90 m
Browse Data-Decorrelation Stretch Product	2	Regional, three images available per scene	15 m (VNIR), 30 m (SWIR), 90 m (TIR)
Surface Reflectance and Surface Radiance	2	16 days required for global coverage; 70 scenes per day	15 m (VNIR), 30 m (SWIR), 90 m (TIR)
Digital Elevation Models (DEMs)	3	Global	30 m
Polar Surface and Cloud Classification Product	4	Regional (poleward from 60° N or S)	30 m over 60 km × 60 km scenes
Surface Emissivity and Surface Kinetic Temperature	2	Regional, land surface	90 m
CERES *Data Set Start Date: February 25, 2000*			
Bi-Directional Scans Product	0,1	Global	20 km at nadir/0.01 second
ERBE-like Instantaneous TOA Estimates	2	Global	20 km at nadir/0.01 second
ERBE-like Monthly Regional Averages (ES-9) and ERBE-like Monthly Geographical Averages (ES-4)	3	Global	2.5°, 5.0°, 10.0°, region and zone, global/monthly (by day and hour)
Single Scanner TOA/ Surface Fluxes and Clouds	2	Global	20 km at nadir/0.01 second
Clouds and Radiative Swath	2	Global	20 km at nadir/0.01 second
Monthly Gridded Radiative Fluxes and Clouds	3	Global	1° region/hour

Terra Data Products

Product Name or Grouping	Processing Level	Coverage	Spatial/Temporal Characteristics
CERES			
Synoptic Radiative Fluxes and Clouds	3	Global	1° region/ 3-hour, month
Average (AVG) (used for the CERES Monthly Regional Radiative Fluxes and Clouds data product); Zonal Average (ZAVG) (used for the CERES Monthly Zonal and Global Radiative Fluxes and Clouds data product)	3	Global	1° region, 1° zone, global/month
Monthly Gridded TOA/Surface Fluxes and Clouds	3	Global	1° region/hour
Monthly TOA/Surface Averages	3	Global	1° region/month
MISR *Data Set Start Date: February 24, 2000*			
Reformatted Annotated Product	1A	Global, daytime; 378-km swath width (nadir), 413-km swath width (off nadir), providing global coverage in 9 days	Spatial sampling of the nadir-viewing camera, 250 m (cross-track) × 275 m (along track); spatial sampling of the 8 off-nadir cameras, 275 m × 275 m. Onboard averaging up to 1.1 km is selectable by ground command.
Radiometric Product	1B1	Global, daytime; 378-km swath width (nadir), 413-km swath width (off nadir), providing global coverage in 9 days	Spatial sampling of the nadir-viewing camera, 250 m (cross-track) × 275 m (along track); spatial sampling of the 8 off-nadir cameras, 275 m × 275 m. Onboard averaging up to 1.1 km is selectable by ground command.
Geo-rectified Radiance Product	1B2	Global, daytime; 378-km swath width (nadir), 413-km swath width (off nadir), providing global coverage in in 9 days	Resampled data, provided on a 275-m × 275-m Space Oblique Mercator grid in certain channels and a 1.1-km × 1.1-km grid in the remaining channels, as established by the instrument observing configuration
Ancillary Geographic Product	1B2	Global, one time only	1.1 km for most surface classification, elevation, and latitude-longitude parameters, 17.6 km for coarse-resolution elevation information
Ancillary Radiometric Product	1B1	N/A, generated periodically	Radiometric calibration coefficients per pixel
Top of Atmosphere (TOA)/ Cloud Product	2, 3	Global, daytime; 9-day for global repeat coverage	1.1, 2.2, 17.6, 35.2, and 70.4-km sampling (various parameters)/ 9-day for global coverage at Level 2; monthly and seasonal globally gridded products at Level 3
Aerosol and Surface Product	2, 3	Global, daytime	1.1, 17.6, and 70.4-km sampling (various parameters)/9-day for global coverage at Level 2; monthly and seasonal globally gridded products at Level 3

Terra Data Products

Product Name or Grouping	Processing Level	Coverage	Spatial/Temporal Characteristics
MISR			
Aerosol Climatology Product	2, 3	N/A, one-time only, with infrequent updates	Contains aerosol particle and mixture microphysical properties
MODIS *Data Set Start Date: February 24, 2000*			
Level 1B Calibrated, Geolocated Radiances	1B	Global	0.25, 0.5, and 1 km/daily (daytime and nighttime)
Geolocation Data Set	1B	Global	1 km /daily (daytime and nighttime)
Aerosol Product	2	Global over oceans, nearly global over land	10 km/daily daytime
Total Precipitable Water	2	Global	Varies with retrieval technique; 1 km near-infrared/daylight only, and 5 km infrared/day and night
Cloud Product	2	Global	1 or 5 km/once or twice per day (varies with parameter)
Atmospheric Profiles	2	Global, clear-sky only	5 km/daily (daytime and nighttime)
Atmosphere Level 2 Joint Product (select subset)	2	Global	5 or 10 km/once or twice per day (varies with parameter)
Atmosphere Level 3 Joint Product	3	Global	1.0° latitude-longitude equal-angle grid/daily, 8-day, and monthly
Cloud Mask	2	Global	250 m and 1 km/daily
Surface Reflectance; Atmospheric Correction Algorithm Products	2	Global land surface	500 m, 0.05°, and 0.25°/daily
Snow Cover	2, 3	Global, daytime	500 m, 0.05°, and 0.25°/daily; 500 m 0.05°/8-day; 0.05°/monthly
Land Surface Temperature (LST) and Emissivity	2, 3	Global land surface	1 km, 5 km/daily; 1 km/8-day
Land Cover/Land Cover Dynamics	3	Global, clear-sky only	1 km and 0.05°/yearly
Vegetation Indices	3	Global land surface	250 m, 500 m, 1 km/16-day; 1 km/ monthly
BRDF/Albedo	3	Global land surface	1 km, 0.05°/16-day
Land Cover Change and Conversion	3, 4	Global, daytime	250 m, 500 m/96-day, yearly

Terra Data Products

Product Name or Grouping	Processing Level	Coverage	Spatial/Temporal Characteristics
MODIS			
Thermal Anomalies/Fire	2, 3	Global, daytime/nighttime	Swath (nominally 1-km) (Level 2); 1 km/daily, 8-day (Level 3)
Leaf Area Index (LAI) and Fraction of Photosynthetically Active Radiation (FPAR)	4	Global	1 km/8-day
Net Photosynthesis and Net Primary Production	4	Global	1 km/8-day, yearly
Sea Surface Temperature (11 μm, day and night; 4 μm, night)	2, 3	Global ocean surface, clear-sky only	1 km/daily (Level 2); 4 km, 9 km/daily, 8-day, monthly, yearly (Level 3)
Sea Ice Cover and Ice-Surface Temperature	2, 3	Global, daytime and nighttime over nonequatorial ocean	1 km, 0.05°/daily
Terra MODIS ocean color products are not available at the time of printing (May 2006); see the ocean color webpage (oceancolor.gsfc.nasa.gov) for up-to-date information regarding the availability of these products.			
MOPITT *Data Set Start Date: March 3, 2000*			
Geolocated Radiances	1B	Global	650-km swath centered at nadir; interlaced crosstrack scan of 4 pixels, each 22 km × 22 km at nadir
CO Profile, CO Column, and CH_4 Column Data	2	Global	CO profiles and column amounts: 22 km at nadir with some degradation depending on cloud clearing and pixel average/daily CH_4 retrievals: currently unavailable
Data Assimilation System (DAS)			
Time-Averaged Single-Level Cloud Quantities	4	Global	1.25° × 1° lon-lat grid (288 × 181 grid points), 8 times/file: 01.30, 04.30, 07.30, 10.30, 13.30, 16.30, 19.30, and 22.30 UTC; 3-hour average centered at the timestamp
Time-Averaged Near Surface and Vertically-Integrated Quantities	4	Global	1.25° × 1° lon-lat grid (288 × 181 grid points), 8 times/file: 01.30, 04.30, 07.30, 10.30, 13.30, 16.30, 19.30, and 22.30 UTC; 3-hour average centered at the timestamp
Time-Averaged 2-Dimensional Surface Data	4	Global	1.25° × 1° lon-lat grid (288 × 181 grid points), 8 times/file: 01.30, 04.30, 07.30, 10.30, 13.30, 16.30, 19.30, and 22.30 UTC; 3-hour average centered at the timestamp
Time-Averaged Surface and Top-of-Atmosphere Stresses	4	Global	1.25° × 1° lon-lat grid (288 × 181 grid points), 8 times/file: 01.30, 04.30, 07.30, 10.30, 13.30, 16.30, 19.30, and 22.30 UTC; 3-hour average centered at the timestamp

Terra Data Products

Product Name or Grouping	Processing Level	Coverage	Spatial/Temporal Characteristics
Data Assimilation System (DAS)			
Time-Averaged 3-Dimensional Cloud Quantities	4	Global	1.25° × 1° lon-lat grid, 36 pressure levels in the vertical (360 × 181 × 36 grid points), 4 times/file 03, 09, 15, and 21 UTC; 6-hour average centered at the timestamp
Time-Averaged 3-Dimensional Wind Tendency Fields	4	Global	1.25° × 1° lon-lat grid, 36 pressure levels in the vertical (360 × 181 × 36 grid points), 4 times/file 03, 09, 15, and 21 UTC; 6-hour average centered at the timestamp
Time-Averaged 3-Dimensional Moisture Tendency Fields	4	Global	1.25° × 1° lon-lat grid, 36 pressure levels in the vertical (360 × 181 × 36 grid points), 4 times/file 03, 09, 15, and 21 UTC; 6-hour average centered at the timestamp
Total Column Ozone	4	Global	2.5° × 2.0° lon-lat grid (144 × 91 grid points), 8 times/file: 00, 03, 06, 09, 12, 15, 18, and 21 UTC; instantaneous data, valid at the timestamp
Instantaneous Near Surface and Vertically-Integrated State Variables	4	Global	1.25° × 1° lon-lat grid (360 × 181 grid points), 8 times/file: 00, 03, 06, 09, 12, 15, 18, and 21 UTC; instantaneous data, valid at the timestamp
Ozone Mixing Ratio	4	Global	2.5° × 2.0° lon-lat grid, 36 pressure levels in the vertical (144 × 91 × 36 grid points), 4 times/file: 00, 06,12, and 18 UTC; instantaneous data, valid at the timestamp
Instantaneous 3-Dimensional State Variables	4	Global	1.25° × 1° lon-lat grid, 36 pressure levels in the vertical (288 × 181 × 36 grid points), 4 times/file: 00, 06,12, and 18 UTC; instantaneous data, valid at the timestamp
Time-Averaged 3-Dimensional Temperature-Tendency Fields	4	Global	1.25° × 1° lon-lat grid, 36 pressure levels in the vertical (288 × 181 × 36 grid points), 4 times/file: 03, 09,15, and 21 UTC; 6-hour average centered at the timestamp
Time-Averaged 3-Dimensional Eddy-Diffusivity and Cloud Max Flux Fields	4	Global	1.25° × 1° lon-lat grid, 36 pressure levels in the vertical (288 × 181 × 36 grid points), 4 times/file: 03, 09,15, and 21 UTC; 6-hour average centered at the timestamp

Terra Data Products

TOPEX/Poseidon

TOPography EXperiment for Ocean Circulation/ Poseidon

TOPEX/Poseidon URLs

sealevel.jpl.nasa.gov/mission/topex.html

Key TOPEX/Poseidon Facts

Joint with France

Orbit
Type: Circular, non-sun-synchronous
Altitude: 1336 km
Inclination: 66°
Period: 112 minutes
Repeat Cycle: 10 days

Mass: 2388 kg

Power: 3,385 W

Design Life: 5 years

Operating Life: Over 13 years, until October 9, 2005

Summary

TOPEX/Poseidon was an oceanography mission to monitor global ocean circulation, improve global climate predictions, and monitor events such as El Niño and ocean eddies. These data have greatly enhanced our understanding of the role of the ocean in the formation of Earth's weather and climate.

Instruments

- Dual-frequency NASA Radar Altimeter (NRA)
- Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS)
- Laser Retroreflector Array (LRA)
- Single-frequency Solid State Radar Altimeter (SSALT, a.k.a. Poseidon-1)
- TOPEX/Poseidon Microwave Radiometer (TMR)
- Turbo Rogue Space Receiver (TRSR) Global Positioning System (GPS) receiver

Points of Contact

- *NASA TOPEX/Poseidon Project Scientist:* Lee-Lueng Fu, NASA Jet Propulsion Laboratory/California Institute of Technology
- *CNES TOPEX/Poseidon Project Scientist:* Yves Menard, CNES Toulouse Space Center

Other Key Personnel

- *TOPEX/Poseidon Program Scientist:* Eric Lindstrom, NASA Headquarters
- *TOPEX/Poseidon Program Executive:* Lou Schuster, NASA Headquarters
- *TOPEX/Poseidon Project Manager:* Mark Fujishin, NASA Jet Propulsion Laboratory/California Institute of Technology

Mission Type

Earth Observation System (EOS) Systematic Measurements

Launch

- *Date and Location:* August 10, 1992, from Kourou, French Guiana
- *Vehicle:* Ariane 42P launch vehicle

Relevant Science Focus Areas

(see NASA's Earth Science Program section)

- Climate Variability and Change
- Water and Energy Cycles

Related Applications

(see Applied Sciences Program section)

- Coastal Management
- Disaster Management

TOPEX/Poseidon Mission Background

TOPEX/Poseidon used the global perspective available only from space to develop maps of ocean topography showing the barely perceptible hills and valleys of the sea surface. This effort significantly expanded the knowledge developed from shipboard research, which is limited to specific locations. From the TOPEX/Poseidon data, scientists calculate the speed and direction of ocean currents worldwide to better understand how the oceans transport heat from Earth's equatorial region toward the poles, thus regulating global climate. The spacecraft's six scientific instruments were designed to function for 3 to 5 years and far exceeded their designed lifetimes. The resulting database helps scientists develop more precise long-term climate forecasts, understand and predict the timing of the El Niño phenomenon, and better comprehend the ocean's role in regulating overall global climate.

TOPEX/Poseidon History

In 1979, NASA's Jet Propulsion Laboratory began planning TOPEX, an ocean topography experiment that would use a satellite altimeter to measure the surface height of the world's oceans. At the same time the French space agency Centre National d'Etudes Spatiales (CNES) was designing an oceanographic mission called Poseidon, named for the Greek god of the sea. The two space agencies decided on a cooperative effort and pooled their resources to form a single mission. The result was the highly successful TOPEX/Poseidon mission, which has achieved science objectives beyond any expectations and at a lower cost than either mission would have cost separately.

TOPEX/Poseidon Data

TOPEX/Poseidon maintained a sea level measurement accuracy of 4.2 cm with global coverage between 66°N and 66°S latitude. Data are available through NASA JPL and CNES and can be found at: sealevel.jpl.nasa.gov/science/data.html.

Data Set Start Date: September 23, 1992

Data Set End Date: October 9, 2005

TOPEX/Poseidon Instruments

TOPEX/Poseidon carried six scientific instruments, four from NASA and two from CNES. A number of these are predecessors of similar instruments now flying on Jason. Additional details can be found in the Jason section.

DORIS (provided by CNES)
Doppler Orbitography and Radiopositioning Integrated by Satellite

DORIS was a precision-orbit-determination system that provided orbital positioning information. An onboard receiver accurately measured the Doppler shift on both transmitted frequencies received from an orbit determination beacon (ODB) station.

LRA (provided by NASA)
Laser Retroreflector Array

LRA reflected laser signals from a network of between 10 and 15 ground laser tracking stations to provide tracking data for precise orbit determination and the altimeter bias calibration.

NRA (provided by NASA)
Dual Frequency NASA Radar Altimeter

NRA was the primary sensor on TOPEX/Poseidon, designed to measure the height of the satellite above the sea at two frequencies—13.6 and 5.3 GHz. This was the first altimeter to use two channels to correct for measurement errors caused by Earth's atmosphere.

SSALT (provided by CNES)
Single-frequency Solid State Radar Altimeter

SSALT (a.k.a, Poseidon-1) was an experimental instrument designed by CNES and intended to validate the accuracy, operation, and signal processing of a small-volume, lightweight, low-power altimeter. Poseidon-1 used the same antenna as the NASA altimeter and had similar operating principles and performance, but it only operated at a single frequency of 13.6 GHz. SSALT (Poseidon-1) was the predecessor of Poseidon-2, which is described in greater detail in the Jason entry.

TOPEX/Poseidon Instruments
(cont.)

TMR (provided by NASA/JPL)
TOPEX/Poseidon Microwave Radiometer

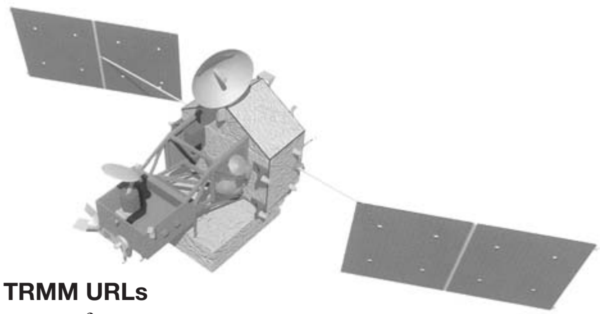
TMR was a three-frequency microwave radiometer that provided total water vapor along the path viewed by the altimeter and was used for range correction. It measured the brightness temperature in the nadir-column at 18, 21, and 37 GHz. JMR on Jason is a slightly more advanced version of TMR.

TRSR (provided by NASA)
Turbo Rogue Space Receiver (TRSR) Global Positioning System (GPS) receiver

TRSR was a high performance GPS receiver designed to provide precise tracking data for precise orbit determination of TOPEX/Poseidon. It measured precision GPS code phase and continuous carrier phase data from up to six GPS satellites.

TRMM

Tropical Rainfall Measuring Mission



TRMM URLs

trmm.gsfc.nasa.gov

www.jaxa.jp/missions/projects/sat/eos/trmm/

Key TRMM Facts

Joint with Japan

Orbit:

Type: Non-sun-synchronous

Altitude: 350 km, boosted to 402 km on August 22, 2001

Inclination: 35°

Period: 91 minutes

Repeat Cycle: Changes 24 hours of local time in 46-day precession cycle

Dimensions: 5.2 m high

Mass: 3512 kg

Power: 1100 W

Design Life: 3 years (now operating for 7 years)

Summary

TRMM is a joint mission between NASA and the Japan Aerospace Exploration Agency (JAXA). It was designed to monitor and study tropical rainfall and the associated release of energy that helps to power the global atmospheric circulation, shaping both weather and climate around the globe.

TRMM was originally designed to carry out a three-year mission, but has operated successfully for over eight years. TRMM completed all of its research and technology objectives by 2001, and continues to provide data used worldwide in the monitoring and forecasting of hazardous weather on a demonstration basis. The TRMM spacecraft is expected to continue until at least 2010, when the core spacecraft for the Global Precipitation Measurement (GPM) mission—a TRMM follow-on—is planned for launch.

Instruments

- Clouds and the Earth's Radiant Energy System (CERES)
- Lightning Imaging Sensor (LIS)
- Precipitation Radar (PR)
- TRMM Microwave Imager (TMI)
- Visible and Infrared Scanner (VIRS)

Points of Contact

- *U.S. TRMM Project Scientist:* Robert Adler, NASA Goddard Space Flight Center
- *U.S. TRMM Deputy Project Scientist:* Arthur Hou, NASA Goddard Space Flight Center
- *Japan TRMM Project Scientist:* Tetsuo Nakazawa, Japan Meteorological Research Institute

Other Key Personnel

- *TRMM Program Scientist:* Ramesh Kakar, NASA Headquarters
- *TRMM Program Executive:* Steve Neeck, NASA Headquarters

Mission Type

Earth Observing System (EOS) Exploratory Mission

Launch

- *Date and Location:* November 27, 1997, from the Tanegashima Space Center, Japan
- *Vehicle:* Japanese H-II F6

Relevant Science Focus Areas

(see NASA's Earth Science Program section)

- Climate Variability and Change
- Water and Energy Cycles
- Weather

Related Applications

(see Applied Sciences Program section)

- Air Quality
- Aviation
- Disaster Management
- Energy Management
- Invasive Species
- Public Health
- Water Management

TRMM Science Goals

- Obtain and study multiyear science data sets of tropical and subtropical rainfall measurements.
- Understand how interactions between the sea, air, and land masses produce changes in global rainfall and climate.
- Improve modeling of tropical rainfall processes and their influence on global circulation in order to predict rainfall and its variability at various periods of time.
- Test, evaluate, and improve satellite rainfall measurement techniques.

TRMM Mission Background

TRMM is a joint mission with Japan launched on November 27, 1997, aboard a Japanese H-II rocket. The TRMM orbit is non-sun-synchronous and initially was at an altitude of 350 km, until the satellite was boosted to 402 km on August 22, 2001. The objectives of TRMM center on rainfall and energy, including latent heat of condensation. The primary rainfall instruments on TRMM are the TRMM Microwave Imager (TMI), the Precipitation Radar (PR), and the Visible and Infrared Scanner (VIRS). Additionally, the TRMM satellite carries two related EOS instruments: The Clouds and the Earth's Radiant Energy System (CERES) and the Lightning Imaging Sensor (LIS).

The combination of satellite-borne passive and active sensors provides critical information regarding the three-dimensional distributions of precipitation and heating in the tropics. Coincident measurements from TMI and PR are complementary: Passive microwave radiometers measure the integrated effects of liquid and ice along the instrument viewing direction while active microwave sensors (radars) provide specific height information on liquid and ice within the cloud.

VIRS adds cloud-top temperatures and structures to complement the descriptions from the radar and radiometer. While direct precipitation information from VIRS is less reliable than that obtained by the microwave sensors, VIRS serves an important role as a bridge between the high-quality but infrequent observations from TMI and PR and the more-frequent observations and longer time series of data available from the geostationary Visible/Infrared (VIS/IR) satellite platforms.

CERES and LIS were designated as EOS instruments and play an important role in rounding out the TRMM science objectives. LIS maps the global frequency of lightning events and plays an important role in coupling the occurrence of lightning to precipitation, thus enhancing our overall understanding both of lightning and of precipitation processes. CERES allows for determination of the total radiant energy balance. Taken together with the latent heating derived from precipitation measurements, a significantly improved picture of the atmospheric energy system can emerge. Unfortunately, an electronics failure limited CERES data collection to the periods of January–August 1998 and March 2000. Fortunately, this captured the peak and decay of the large 1998 El Niño event, and provided a calibration overlap with the Terra Mission.

TRMM Instruments

CERES
Clouds and the Earth's Radiant Energy System

A three-channel, broadband radiometer (0.3 to > 100 μm, 0.3–5 μm, 8–12 μm) designed to measure major elements of the Earth's radiation balance.

LIS
Lightning Imaging Sensor

Staring telescope/filter imaging system (0.777 μm) with 5-km spatial resolution and 2-ms temporal resolution over an imaging area of 600 km × 600 km.

PR
Precipitation Radar

An electronically scanning radar operating at 13.8 GHz; 4.3-km instantaneous field-of-view at nadir; 220-km swath. Provided by JAXA.

TMI
TRMM Microwave Imager

A nine-channel conical scanning passive microwave imager making measurements from 10 to 85 GHz, 37- to 4.6-km resolution respectively, covering 760-km swath.

VIRS
Visible and Infrared Scanner

A five-channel cross-track imaging radiometer (0.62, 1.63, 3.78, 10.83, and 12.03 μm) with nominal 2-km resolution at nadir and 720-km swath.

TRMM data are sent to the NASA TRMM Science Data and Information System (TSDIS) at NASA GSFC via the Tracking and Data Relay Satellite System (TDRSS) and the White Sands Receiving Station. GSFC is responsible for all science data processing and data distribution to the TRMM algorithm development team. Upon data product generation, the data are sent to the GSFC Earth Sciences Distributed Active Archive Center (GES DAAC) for archiving and distribution to the general user community.

CERES

Clouds and the Earth's Radiant Energy System

The CERES instrument is described in the Aqua section.

LIS

Lightning Imaging Sensor

Investigates the distribution and variability of lightning over Earth with storm-scale spatial resolution.

LIS Background

LIS is designed to investigate the global incidence of lightning, its correlation with convective rainfall, and its relationship with the global electric circuit. Conceptually, LIS is a simple device, consisting of a staring imager optimized to locate both intracloud and cloud-to-ground lightning with storm-scale resolution over a large region of Earth's surface, to mark the time of occurrence, and to measure the radiant energy. It will monitor individual storms within the field of view (FOV) for 80 seconds, long enough to estimate the lightning flash rate. Location of lightning flashes is determined to within 5 km over a 600-km × 600-km FOV.

The LIS design uses an expanded optics wide-FOV lens, combined with a narrow-band interference filter that focuses the image on a small, high-speed, charge-coupled-device focal plane. The signal is read out from the focal plane into a real-time data processor for event detection and data compression. The particular characteristics of the sensor design result from the requirement to detect weak lightning signals during the day when the background illumination, produced by sunlight reflecting from the tops of clouds, is much brighter than the illumination produced by the lightning.

A combination of four methods is used to take advantage of the significant differences in the temporal, spatial, and spectral characteristics between the lightning signal and the background noise. First, spatial filtering is used to match the instantaneous FOV of each detector element in the LIS focal-plane array to the typical cloud-top area illuminated by a lightning event (about 5 km). Second, spectral filtering is applied, using a narrow-band interference filter centered about the strong hypoiodite ion (OI) emission multiplet in the lightning spectrum at 777.4 nm. Third, temporal filtering is applied. The lightning pulse duration is of the order of

Key LIS Facts

Provided by NASA Marshall Space Flight Center (MSFC)

Heritage: Optical Transient Detector

Instrument Type: Staring telescope/filter imaging system that detects the rate, location, and radiant energy of lightning flashes

Swath: 600 km × 600 km

Spatial Resolution: 5 km

Temporal Resolution: 2 ms

Wavelength: Operating at 0.7774 μm

Dimensions:

Sensor head assembly (cylindrical): 20 cm × 30 cm

Electronics Assembly: 30 cm × 20 cm × 30 cm

Mass: 20 kg

Duty Cycle: 100%

Power: 33 W

Data Rate: 6 Kbps

Thermal Control: Heater, radiator

Thermal Operating Range: 0–40° C

Field of View (FOV): 80° × 80°

Instrument IFOV: 0.7°

Direct Broadcast: No

400 μs, whereas the background illumination tends to be constant on a time scale of seconds. The lightning signal-to-noise ratio improves as the integration time approaches the pulse duration. Accordingly, an integration time of 2 ms is chosen to minimize pulse splitting between successive frames and to maximize lightning detectability. Finally, a modified frame-to-frame background subtraction is used to remove the slowly varying background signal from the raw data coming off the LIS focal plane. If, after background removal, the signal for a given pixel exceeds a specified threshold, that pixel is considered to contain a lightning event.

LIS investigations are striving to understand processes related to, and underlying, lightning phenomena in the Earth atmosphere system. These processes include the amount, distribution, and structure of deep convection on a global scale, and the coupling between atmospheric dynamics and energetics as related to the global distribution of lightning activity. The investigations will contribute to a number of important EOS mission objectives, including cloud characterization and hydrologic-cycle studies. Lightning activity is closely coupled to storm convection, dynamics, and microphysics, and can be correlated to the global rates, amounts, and distribution of convective precipitation, to the release and transport of latent heat, and to the chemical cycles of carbon, sulfur, and nitrogen. LIS standard products include intensities, times of occurrence, and locations of lightning events.

The performance of LIS has exceeded specifications and has been returning unprecedented data on lightning activity. LIS is enabling investigators to quantify relationships between lightning, convection, and ice production.

LIS Principal Investigator

Hugh Christian, NASA Marshall Space Flight Center

LIS URL

thunder.msfc.nasa.gov/lis.html

PR

Precipitation Radar

Measures the three-dimensional (3-D) rainfall distribution over both land and ocean, and defines the layer depth of the precipitation.

PR is the first spaceborne instrument designed to provide 3-D maps of storm structure. The measurements yield invaluable information on the intensity and distribution of the rain, the rain type, the storm depth and the height at which the snow melts into rain. The estimates of the heat released into the atmosphere at different heights based on these measurements can be used to improve models of the global atmospheric circulation.

PR has a horizontal resolution at the ground of about 4 km and a swath width of 220 km. One of its most important features is its ability to provide vertical profiles of the rain and snow from the surface to a height of about 20 km. PR is able to detect fairly

Key PR Facts

Provided by Japan (JAXA)

Heritage: 1st space-borne precipitation radar

Instrument Type: 128-element active phased array system

Scan Type: Cross-track

Swath: 220 km

Observable Range: Surface to 15-km altitude

Range Resolution: 250 km

Horizontal Resolution: 4.3 km (nadir)

Vertical Resolution: 0.25 km (nadir)

Frequency: 13.8 GHz horizontal polarization

Dimensions: 2.3 m × 2.3 m × 0.7 m (platform and antenna)

Power: 224 W

Data Rate: 93.2 Kbps

Number of Independent Samples: 64

Direct Broadcast: No

light rain rates down to about 0.7 mm/hr. For intense rain rates, where the attenuation effects can be strong, new methods of data processing have been developed that help correct for this effect. PR is able to separate out rain echoes for vertical sample sizes of about 250 m when looking straight down.

PR Project Scientist (Japan)

Kenichi Okamoto, Communications Research Laboratory

TMI

TRMM Microwave Imager

Provides information on the integrated column precipitation content, cloud liquid water, cloud ice, rain intensity, and rainfall types.

TMI is a passive microwave radiometer designed to provide quantitative rainfall information over a wide swath. By carefully measuring the minute amounts of microwave energy emitted by Earth and its atmosphere, TMI is able to quantify the water vapor, the cloud water, and the rainfall intensity in the atmosphere. It is a relatively small instrument that consumes little power. This, combined with the wide swath and the good, quantitative information regarding rainfall, makes TMI the "workhorse" of the rain-measuring package on TRMM.

Improving on History

TMI is not a new instrument. It is based on the design of the highly successful Special Sensor Microwave Imager (SSM/I) which has been flying continuously on satellites of the Defense Meteorological Satellite Program (DMSP) since 1987. TMI measures the intensity of radiation at five separate frequencies: 10.7, 19.4, 21.3, 37, and 85.5 GHz. These frequencies are similar to those of the SSM/I, except that TMI has the additional 10.7-GHz channel designed to provide a more-linear response for the high rainfall rates common in tropical regions. The other main improvement is due to improved ground resolution. This improvement, however, is not the result of any instrument improvements, but rather a function of the lower altitude of TRMM (350 km compared to 860 km of SSM/I). TMI has a 760-km-wide swath on the surface. The higher resolution of TMI, as well as the additional 10.7 GHz frequency, make TMI a better instrument than its predecessors. The additional information supplied by PR further helps to improve algorithms. The improved rainfall products over a wide swath complement and enhance the continuing measurements being made by the SSM/I and future radiometers as well as being an integral part of the TRMM efforts.

Measuring Rainfall with Microwaves

Calculating rainfall rates using a passive microwave instrument like TMI is not a trivial task. It requires some fairly complicated calculations, the physical basis of which is the Planck radiation law.

Key TMI Facts

Provided by NASA Goddard Space Flight Center (GSFC)

Heritage: Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave Imager (SSM/I)

Instrument Type: Multichannel passive microwave radiometer

Scanning Mode: Conical

Incidence Viewing: Incident Angle equals 52.8° (at 350 km)

FOV: Channel dependent (IFOV given below applies to the 350-km orbit)

Instrument IFOV:
- Ch 1–2: 60 km × 36 km;
- Ch 3–4: 31 km × 18 km;
- Ch 5: 27 km × 17 km;
- Ch 6–7: 16 km × 10 km;
- Ch 8–9: 7 km × 4 km

Swath: 760 km (on beam centers)

Spatial Resolution: Approximately equals IFOVs

Frequency: 10.65, 19.35, 37.0, and 85.5 GHz at dual polarization and 22.235 GHz at vertical polarization

Dimensions: Instrument electronics housed in a drum-shaped housing about 40-cm diameter by 40 cm height, with the antenna reflector (65 cm × 61 cm) attached to the top of the drum (focal length 51 cm, F/D = 0.348) and the whole instrument spinning at 32 rpm

Mass: 54.1 kg

Power: 66.5 W

Duty Cycle: Continuous

Data Rate: 8.5 kbps

Direct Broadcast: No

Planck's law tells us how much energy a hypothetical body that absorbs all the radiation incident upon it would emit. Of course, real world objects don't absorb all the energy incident upon them. So Planck's law has to be combined with laws that govern electromagnetic wave interactions with particles and surfaces, e.g., absorption and scattering, to determine exactly how much energy a given object will emit. The amount of radiation emitted is a function of the temperature of the surface and also of the wavelength of the radiation. This function is a very useful relationship to use in remote sensing. It means that if we measure how much energy a surface emits, we can invert Planck's law and solve for the temperature of the surface. For microwave radiation, the amount of energy emitted also depends on the state of surface. This means that a surface composed of air will behave very differently than a surface composed of water, or a surface composed of rock and soil.

Surfaces such as lakes and oceans only emit about one-half the microwave energy that Planck's law would predict they should. Therefore when a water surface is viewed by a passive microwave radiometer, the surface appears to be very 'cold' relative to its actual temperature. The temperature that the radiometer observes is referred to as the 'brightness temperature' of the surface, and in the case of water, is about one-half the value of the actual temperature of the surface. In contrast, raindrops in the atmosphere absorb the emission from the water surface below them and reemit the radiation at a much warmer temperature. This means that raindrops will appear warmer than the colder water surface when viewed by a passive microwave sensor. Therefore when viewing a body of water, we can conclude that the higher the brightness temperature of the scene, the more raindrops are present, i.e., the more intense the precipitation is in that region. Research over the past three decades has made it possible to obtain fairly accurate rainfall estimates over water surfaces based on the brightness temperature of the scene.

Land surfaces have very different physical properties than water surfaces. The brightness temperature of a land surface is usually about 90% of the actual surface temperature. This means that the contrast between the surface and raindrops for land surfaces is nowhere near as large as it is for water surfaces. However, certain properties of rainfall can still be inferred over land surfaces using passive microwave techniques. High frequency microwaves (as measured by the 85.5 GHz channel on TMI) are strongly scattered by the ice present in many rain clouds. This reduces the microwave signal at the sensor and offers a contrast against the warm land background.

TMI Project Scientist

James Shiue, NASA Goddard Space Flight Center

Key VIRS Facts

Provided by NASA GSFC

Heritage: Advanced Very High Resolution Radiometer (AVHRR)

Instrument Type: Scanning radiometer

Scan Type: Cross-track

FOV: +45°

Instrument IFOV: 6.02 mrad

Swath Width: 720 km; post-boost: 833 km

Spatial Resolution: 2.2 km; post-boost: 2.4 km

Wavelength: 0.63, 1.6, 3.75, 10.8, 12.0 μm

Dimensions: 103 cm × 96 cm × 52 cm

Mass: 48.6 kg

Power: 51.2 W

Duty Cycle: 100%

Data Rate: 49.8 Kbps (day), 28.8 Kbps (night)

Direct Broadcast: No

VIRS

Visible and Infrared Scanner

Provides high-resolution observations of cloud coverage, cloud type, and cloud-top temperature/height.

VIRS Background

VIRS is one of the three instruments in the rain-measuring package on TRMM and provides a very indirect indicator of rainfall. It also ties TRMM measurements to other measurements that are made routinely using the meteorological Polar-orbiting Operational Environmental Satellite System (POESS) and those that are made using the Geostationary Operational Environmental Satellites (GOES) operated by the United States.

VIRS senses radiation coming from Earth in five spectral regions, ranging from visible to infrared, at wavelengths of 0.63–12 µm. VIRS is included in the primary instrument package on TRMM because of its ability to delineate rainfall, but even more importantly, because it serves as a transfer standard to other measurements that are made routinely using the POESS and GOES satellites. The intensity of the radiation in the various spectral regions (or bands) can be used to determine the reflectance (visible and near infrared) or brightness temperature (infrared) of the scene.

If the sky is clear, the temperature will correspond to that of the surface of Earth, and, if there are clouds, the temperature will tend to be that of the cloud tops. Colder temperatures will produce greater intensities in the shorter wavelength bands, and warmer temperatures will produce greater intensities in the longer wavelength bands. Since colder clouds occur at higher altitudes the measured temperatures are useful as indicators of cloud heights, and the highest clouds can be associated with the presence of rain.

A variety of techniques use the infrared (IR) images from VIRS to estimate precipitation. Higher cloud tops are positively correlated with precipitation for convective clouds (generally thunderstorms), which dominate tropical (and therefore global) precipitation accumulations. One notable exception to this correlation is with the high cirrus clouds that generally flow out of thunderstorms. These cirrus clouds are high and therefore 'cold' in the infrared observations, but they do not rain. To differentiate these cirrus clouds from water clouds (cumulonimbus), a technique, which involves comparing the two infrared channels at 10.8 and 12.0 µm, is employed. However, IR techniques usually have significant errors for instantaneous rainfall estimates. The strength of infrared observations lies in the ability to monitor the clouds continuously from geostationary altitude. By comparing the visible and infrared observations from TRMM with the rainfall estimates of TMI and PR, scientists hope to learn much more about the relationship of the cloud tops as seen from geostationary orbit.

VIRS uses a rotating mirror to scan across the track of the TRMM observatory, thus sweeping out a region 720 km wide as the observatory proceeds along its orbit. Looking straight down (nadir), VIRS can pick out individual cloud features as small as 2 km.

VIRS Project Scientist

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VIRS Instrument Scientist

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TRMM References

CERES References

See the Aqua section for a list of CERES references.

LIS References

Boccippio, D. J., S. J. Goodman, and S. Heckman, 2000: Regional differences in tropical lightning distributions. *J. Appl. Met.*, **39**, 2231–2248.

Boccippio, D. J., W. J. Koshak, and R. J. Blakeslee, 2002: Performance assessment of the Optical Transient Detector and Lightning Imaging Sensor: 1. Predicted diurnal variability. *J. Atmos. Oceanic Tech.*, **19**, 1318–1332.

Christian, H. J., R. J. Blakeslee, D. J. Boccippio, W. L. Boeck, D. E. Buechler, K. T. Driscoll, S. J. Goodman, J. M. Hall, W. J. Koshak, D. M. Mach, and M. F. Stewart, 2003: Global frequency and distribution of lightning as observed by the Optical Transient Detector. *J. Geophys. Res.*, **108(D1)**, 4005–4119, 4004, doi: 10.1029/2002JD002347.

Christian, H. J., R. J. Blakeslee, S. J. Goodman, D. M. Mach, M. F. Stewart, D. E. Buechler, W. J. Koshak, J. M. Hall, K. T. Driscoll, and D. J. Boccippio, 1999: The Lightning Imaging Sensor. *Proc. 11th International Conference on Atmospheric Electricity (NASA)*, Guntersville, Alabama, 746–749.

Christian, H. J., R. J. Blakeslee, S. J. Goodman, and D. Mach, eds., 2000: Algorithm Theoretical Basis Document (ATBD) for the Lightning Imaging Sensor, 53 pp. [Available online at: thunder.msfc.nasa.gov/bookshelf/pubs/atbd-lis-2000.pdf.]

Christian, H. J., R. J. Blakeslee, and S. J. Goodman, 1992: Lightning Imaging Sensor (LIS) for the Earth Observing System. NASA Technical Memorandum 4350, 44. [Available from Center for Aerospace Information, P.O. Box 8757, Baltimore-Washington International Airport, Baltimore, MD 21240.]

Koshak, W. J., J. W. Bergstrom, M. F. Stewart, H. J. Christian, J. M. Hall, and R. J. Solakiewicz, 2000: Laboratory calibration of the Optical Transient Detector and Lightning Imaging Sensor. *J. Atmos. Oceanic Tech.*, **17**, 905–915.

PR References

Awaka, J., T. Iguchi, and K. Okamoto, 1998: Early results on rain type classification by the Tropical Rainfall Measuring Mission (TRMM) precipitation radar. *Proc. 8th URSI Commission F Open Symposium*. Aveiro, Portugal, pp. 143–146.

Iguchi, T., T. Kozu, R. Meneghini, J. Awaka, and K. Okamoto, 2000: Rain profiling algorithm for the TRMM Precipitation Radar. *J. Appl. Meteor.*, **39**, 2038–2052.

Kozu, T., T. Kawanishi, H. Kuroiwa, M. Kojima, K. Oikawa, H. Humagai, K. Okamoto, M. Okumura, H. Nakatsuka, and K. Nishikawa, 2001: Development of Precipitation Radar onboard the Tropical Rainfall Measuring Mission (TRMM) Satellite. *IEEE Trans. Geosci. Remote Sens.*, **39**, 102–116.

Meneghini, R., T. Iguchi, T. Kozu, L. Liang, K. Okamoto, J. A. Jones, and J. Kwiatkowski, 2000: Use of the surface reference technique for path attenuation estimates from the TRMM Precipitation Radar. *J. Appl. Meteor.*, **39**, 2053–2070.

Meneghini, R., J. A. Jones, T. Iguchi, K. Okamoto, and J. Kwiatkowski, 2001: Statistical methods of estimating average rainfall over large space-timescales using data from the TRMM Precipitation Radar. *J. Appl. Meteor.*, **40**, 568–585.

Okamoto, K., 2003: A short history of the TRMM Precipitation Radar. In W-K. Tao and R. Adler, eds., *Cloud Systems, Hurricanes, and the Tropical Rainfall Measuring Mission*, American Meteorological Society, Boston, Massachusetts, 234 pp, Chapter 16.

TMI Reference

Kummerow, C, W. Barnes, T. Kozu, J.Shiue, and J. Simpson, 1998: The Tropical Rainfall Measuring Mission (TRMM) sensor package. *J. Atmos. Oceanic Tech.*, **15**, 809–817.

VIRS References

Barnes, R., W. Barnes, C. Lyu, and J. Gales, 2000: An overview of the Visible and Infrared Scanner radiometric calibration algorithm. *J. Atmos. Oceanic. Tech.*, **17(4)**, 395–405.

Lyu, C., W. Barnes, and R. Barnes, 2000: First results from the on-orbit calibrations of the Visible and Infrared Scanner for the Tropical Rainfall Measuring Mission. *J. Atmos. Oceanic. Tech.*, **17(4)**, 385–394.

Lyu, C., and W. Barnes, 2003: Four years of TRMM/VIRS on-orbit calibration and performance using lunar models and data from Terra/MODIS. *J. Atmos. Oceanic. Tech.*, **20(3)**, 333–347.

TRMM Data Products

For more information about the data products please see *The EOS Data Products Handbook, Volume 1* (revised January 2004) available at: eos.nasa.gov/eos_homepage/for_scientists/data_products/

Product Name or Grouping	Processing Level	Coverage	Spatial/Temporal Characteristics
CERES *Data Set Start Date: December 28, 1997; Data Set End Date: March 2000 (only intermittent data starting September 1, 1998)*			
Bi-Directional Scans Product	0, 1	Global for latitudes 40°N – 40°S	20 km at nadir/0.01 second
ERBE-like Instantaneous TOA Estimates	2	Global, 40°N – 40°S	20 km at nadir/0.01 second
ERBE-like Monthly Regional Averages (ES-9) and ERBE-like Monthly Geographical Averages (ES-4)	3	Global, 40°N – 40°S	2.5°, 5.0°, 10.0°, region and zone, global/ monthly (by day and hour)
Single Scanner TOA/Surface Fluxes and Clouds	2	Global, 40°N – 40°S	20 km at nadir/0.1 second
Clouds and Radiative Swath	2	Global, 40°N – 40°S	20 km at nadir/0.1 second
Monthly Gridded Radiative Fluxes and Clouds	3	Global, 40°N – 40°S	1° region/hourly
Synoptic Radiative Fluxes and Clouds	3	Global, 40°N – 40°S	1° region/3-hour, monthly
Average (AVG) (used for the CERES Monthly Regional Radiative Fluxes and Clouds data product) and Zonal Average (ZAVG) (used for the CERES Monthly Zonal and Global Radiative Fluxes and Clouds data product)	3	Global, 40°N – 40°S	1° region, 1° zone, global/monthly
Monthly Gridded TOA/Surface Fluxes and Clouds	3	Global, 40°N – 40°S	1° region/hourly
Monthly TOA/Surface Averages	3	Global, 40°N – 40°S	1° region/monthly
LIS *Data Set Start Date: December 1, 1997*			
500 km × 500 km Equal Area Monthly Grid	2	Global, 35°N – 35°S	4 km × 4 km pixel at nadir, orbit granules/ 2 ms resolution; 2.5 × 2.5 monthly, 47-day moving average
Orbit Attributes	3	Global, 35°N – 35°S moving average	4 km × 4 km pixel at nadir, orbit granules/ 2 ms resolution; 2.5 × 2.5 monthly, 47-day
Threshold Attributes	3	Global, 35°N – 35°S moving average	4 km × 4 km pixel at nadir, orbit granules/ 2 ms resolution; 2.5 × 2.5 monthly, 47-day
Browse Area	3	Global, 35°N – 35°S moving average	4 km × 4 km pixel at nadir, orbit granules/ 2 ms resolution; 2.5 × 2.5 monthly, 47-day

TRMM Data Products

Product Name or Grouping	Processing Level	Coverage	Spatial/Temporal Characteristics
LIS *(cont.)*			
Vector Statistics	3	Global, 35°N – 35°S	4 km × 4 km pixel at nadir, orbit granules/ 2 ms resolution; 2.5 × 2.5 monthly, 47-day moving average
Metadata Description	3	Global, 35°N – 35°S	4 km × 4 km pixel at nadir, orbit granules/ 2 ms resolution; 2.5 × 2.5 monthly, 47-day moving average
Summary Data	3	Global, 35°N – 35°S	4 km × 4 km pixel at nadir, orbit granules/ 2 ms resolution; 2.5 × 2.5 monthly, 47-day moving average
Flash Rate Data	3	Global, 35°N – 35°S	4 km × 4 km pixel at nadir, orbit granules/ 2 ms resolution; 2.5 × 2.5 monthly, 47-day moving average
Ephemeris Data	3	Global, 35°N – 35°S	4 km × 4 km pixel at nadir, orbit granules/ 2 ms resolution; 2.5 × 2.5 monthly, 47-day moving average
Event Rate Sets	3	Global, 35°N – 35°S	4 km × 4 km pixel at nadir, orbit granules/ 2 ms resolution; 2.5 × 2.5 monthly, 47-day moving average
PR *Data Set Start Date: December 7, 1997*			
Radar Total Power, Noise, and Reflectivity	1B	36°S – 36°N; 15–16 orbits per day with a swath width of 220 km before August 2001 and 253 km after August 2001	5 km (after August 2001)
Rain Occurrence and Rain Type and Bright Band Height	2	36°S – 36°N; 15–16 orbits per day with a swath width of 220 km before August 2001 and 253 km after August 2001	5 km (after August 2001)
Surface Cross-Section as Function of Scan Angle	2	36°S – 36°N; 15–16 orbits per day with a swath width of 220 km before August 2001 and 253 km after August 2001	5 km (after August 2001)
Range Profiles of Rain and Water Content	2	36°S – 36°N; 15–16 orbits per day with a swath width of 220 km before August 2001 and 253 km after August 2001	5 km (after August 2001)

TRMM Data Products

Product Name or Grouping	Processing Level	Coverage	Spatial/Temporal Characteristics
TMI *Data Set Start Date: December 7, 1997*			
Monthly Accumulated Rainfall and Vertical Structure, Monthly Combined Accumulated Surface Rainfall	3	40°N – 40°S	5° × 5° and 0.5° × 0.5°/monthly
Calibrated Brightness Temperatures	1B	38°S – 38°N; 15–16 orbits per day with a swath width of 760 km before August 2001 and 875 km after August 2001	5 km
Surface Rainfall and Vertical Structure	2	38°S – 38°N; 15–16 orbits per day with a swath width of 760 km before August 2001 and 874 km after August 2001	5 km
Monthly Surface Rainfall	3	40°N – 40°S over oceans only	5° × 5° and 0.5° × 0.5°/monthly
TRMM			
Instantaneous Radar Site Rain Map	2A	150-km radius of ground validation radar, continuous	2 km (minimum)
Instantaneous Radar Site Convective/Stratiform Map	2A	150-km radius of ground validation radar, continuous	2 km (minimum)
Instantaneous Radar Site 3-D Reflectivities	2A	150-km radius of ground validation radar, continuous	2 km (minimum)
Combined Surface Rainfall Rate and Vertical Structure	2	36°S – 36°N; 15–16 orbits per day with a swath width of 220 km before August 2001 and 253 km after August 2001	5 km (after August 2001)
Monthly Combined Accumulated Rainfall and Vertical Structure	3	Day and Night, 40°N – 40°S	5° × 5°, 14 levels/monthly
1° Daily Combined Rainfall and Monthly Combined Instrument Rainfall	4	Day and Night, 40°N – 40°S	1° × 1°/daily, monthly
5-Day Site Rain Map	3	150-km radius of ground validation radar, continuous	2 km × 2 km/5-day accumulation

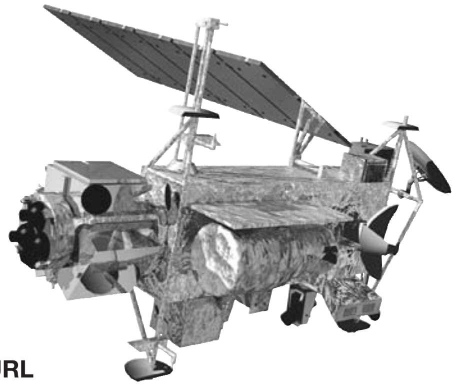
TRMM Data Products

Product Name or Grouping	Processing Level	Coverage	Spatial/Temporal Characteristics
TRMM *(cont.)*			
30-Day Site Rain Map	3	150-km radius of ground validation radar, continuous	2 km × 2 km/30-day accumulation
Monthly 3-D Structure	3	150-km radius of ground validation radar, continuous	2 km × 2 km/30-day accumulation
VIRS *Data Set Start Date: December 7, 1997*			
Calibrated Radiances	1B	38°S – 38°N; 15–16 orbits per day with a swath width of 720 km before August 2001 and 830 km after August 2001	2 km

TRMM Data Products

UARS

Upper Atmosphere Research Satellite



UARS URL
umpgal.gsfc.nasa.gov/

Key UARS Facts

Orbit:
Type: Non-sun-synchronous
Inclination: 57°
Altitude: 585 km
Period: 96.7 minutes

Dimensions: ~11 m × ~4.5 m

Mass: 5896.7 kg

Design Life: 3 years

Operating Status: Decommissioned on December 14, 2005

Summary

UARS measures ozone and chemical compounds found in the ozone layer that affect ozone chemistry and processes. UARS also measures winds and temperatures in the stratosphere and the energy input from the Sun. Together, these measurements help define the role of the upper atmosphere in climate and climate variability.

Instruments

- Active Cavity Radiometer Irradiance Monitor II (ACRIM II)
- Cryogenic Limb Array Etalon Spectrometer (CLAES)
- Halogen Occultation Experiment (HALOE)
- High Resolution Doppler Imager (HRDI)
- Improved Stratospheric and Mesospheric Sounder (ISAMS)
- Microwave Limb Sounder (MLS)
- Particle Environment Monitor (PEM)
- Solar Stellar Irradiance Comparison Experiment (SOLSTICE)
- Solar Ultraviolet Spectral Irradiance Monitor (SUSIM)
- Wind Imaging Interferometer (WINDII)

Point of Contact

- *UARS Project Scientist:* Charles Jackman, NASA Goddard Space Flight Center

Mission Type

Earth Observing System (EOS) Systematic Measurements

Launch

- *Date and Location:* September 12, 1991, from Kennedy Space Center, Florida
- *Vehicle:* Space Shuttle Discovery

Relevant Science Focus Area

(see NASA's Earth Science Program section)

- Atmospheric Composition

Related Applications

(see Applied Sciences Program section)

- Air Quality
- Carbon Management
- Public Health

UARS Mission Objectives

The UARS mission objectives include the study of:
- Upper atmosphere energy input and loss;
- Upper atmosphere global photochemistry;
- Upper atmosphere dynamics;
- Coupling among these processes; and
- Coupling between the upper and lower atmosphere.

UARS Mission Background

The goal of upper-atmosphere research is to understand the chemistry, dynamics, and energy balance above the troposphere as well as the coupling among the relevant processes and among the different regions of the atmosphere. This implies an understanding of the mechanisms that control upper-atmosphere structure and variability, as well as an understanding of how the upper atmosphere responds to natural and man-made causes. Together, these will help define the role of the upper atmosphere in climate and climate variability. The UARS platform provides simultaneous, coordinated measurements of atmospheric internal structure (trace constituents, physical dynamics, radiative emission, thermal structure, density) and measurements of some of the external influences acting upon the upper atmosphere (solar radiation and energetic particles). In addition, the combination of orbit and instrument design provides nearly global coverage.

UARS History

UARS was the first NASA mission to carry out a systematic, comprehensive study of the stratosphere and it continued to furnish important new data on the mesosphere and thermosphere until mid-December 2005. Following the deployment of UARS on September 15, 1991 from the Space Shuttle Discovery, scientists have gained a better understanding of the energy input, chemistry, and dynamics of the upper atmosphere and the coupling between the upper and lower atmosphere. UARS focuses on the processes that lead to ozone depletion, complementing and amplifying the measurements of total ozone made by the Total Ozone Mapping Spectrometer (TOMS) previously flown on NASA's Nimbus-7 spacecraft and on the Russian Meteor-3 spacecraft, and currently flying on NASA's Earth Probe spacecraft. UARS also measures winds and temperatures in the stratosphere as well as the energy input from the Sun.

Ten UARS instruments have provided the most complete dataset on upper-atmospheric energy inputs, winds, and chemical composition ever gathered. Together, these observations constitute a highly integrated investigation of the nature of the upper atmosphere and help define the role of the upper atmosphere in climate and climate variability. In its first two weeks of operation, UARS data confirmed the polar-ozone-depletion theories by providing three-dimensional maps of ozone and chlorine monoxide near the South Pole during development of the 1991 ozone hole. Despite the design life of only 3 years, five out of ten instruments onboard UARS—HALOE, HRDI, PEM, SOLSTICE, and SUSIM—continued to operate into 2005, prior to decommissioning of the satellite in December 2005.

UARS Data

UARS data are available at: daac.gsfc.nasa.gov/guides/GSFC/guide/UARS_project.gd.html.

UARS collected data on the chemistry, dynamics, and radiative inputs to the upper atmosphere far beyond its designed lifetime, obtaining over 13 years of observations for many atmospheric constituents, temperature, winds, and external forcings.

UARS Instruments

The ten UARS instruments were designed to obtain measurements of chemical species composition, temperature, winds, and energy inputs of the upper atmosphere.

Four UARS instruments were devoted to measuring constituents, spectroscopically determining the concentrations of many different chemical species and deriving the variation of atmospheric temperature with altitude by observing infrared emissions from carbon dioxide. These are:

CLAES
Cryogenic Limb Array Etalon Spectrometer

HALOE
Halogen Occultation Experiment

ISAMS (provided by the U.K.)
Improved Stratospheric and Mesospheric Sounder

MLS
Microwave Limb Sounder

Two instruments, utilizing high-resolution interferometry, measure upper-atmosphere winds by sensing the Doppler shift in light absorbed by, or emitted from, atmospheric molecules. These are:

HRDI
High Resolution Doppler Imager

WINDII (provided by Canada)
Wind Imaging Interferometer

Four additional instruments obtained estimates of the energy incident on the atmosphere by measuring solar ultraviolet radiation and the flux of charged particles from Earth's magnetosphere. These are:

ACRIM II
Active Cavity Radiometer Irradiance Monitor II

PEM
Particle Environmental Monitor

SOLSTICE
Solar Stellar Irradiance Comparison Experiment

SUSIM
Solar Ultraviolet Spectral Irradiance Monitor

Note: ACRIM II was not officially part of the UARS project. It was included on the UARS platform as an instrument of opportunity.

Data Set Start Dates:

CLAES	October 25, 1991
HALOE	October 11, 1991
HRDI	November, 6, 1991
ISAMS	September 26, 1991
MLS	September 18, 1991
PEM	October 1, 1991
SOLSTICE	October 3, 1991
SUSIM	October 12, 1991
WINDII	November 4, 1991

Data Set End Date: December 14, 2005

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Acronyms and Abbreviations

2DSTAR Two-dimensional ESTAR

3-D Three-dimensional

A

A-Train Afternoon Constellation (EOS)

AAOE Airborne Antarctic Ozone Experiment

AASE II Airborne Arctic Stratospheric Expedition II

AASI AMSR-E Antarctic Sea Ice validation campaign

AATSR Advanced Along Track Scanning Radiometer

AC Atmospheric Corrector

ACCESS Advancing Collaborative Connections for Earth System Science

ACE Atmospheric Chemistry Experiment

ACR Active-Cavity Radiometer

ACRIM Active Cavity Radiometer Irradiance Monitor

ACRIMSAT Active Cavity Radiometer Irradiance Monitor Satellite

ACSYS Arctic Climate System Study

ACT ATI Component Technology

A/D Alternating/Direct

ADEOS Advanced Earth Observing Satellite (Japan) *(ADEOS renamed Midori)*

AERONET Aerosol Robotic Network

AES Airborne Emission Spectrometer

AESOPS Antarctic Environment and Southern Ocean Process Study

AETD Applied Engineering and Technology Directorate (NASA)

AGS Alaska Ground Station (in Poker Flats)

AGU American Geophysical Union

AIAA American Institute of Aeronautics and Astronautics

AirMISR Airborne Multi-angle Imaging Spectroradiometer

AIRS Atmospheric Infrared Sounder

AIRSAR Airborne Synthetic Aperture Radar

AIST Advanced Information Systems Technology

ALI Advanced Land Imager

ALOS Advanced Land Observation Satellite (JAXA)

ALT Altimeter

A AMI Active Microwave Instrument

AMMR Airborne Multi-channel Microwave Radiometer

AMR Advanced Microwave Radiometer

AMS American Meteorological Society

AMSR Advanced Microwave Scanning Radiometer

AMSR-E Advanced Microwave Scanning Radiometer for EOS

AMSU Advanced Microwave Sounding Unit

AMTS Advanced Moisture and Temperature Sounder

AO Announcement of Opportunity

APL Applied Physics Laboratory (Johns Hopkins University)

APS Aerosol Polarimetry Sensor

ArboNet Arbovirus Surveillance Network

ARC Ames Research Center

ARM Atmospheric Radiation Measurement program

ASAR Advanced Synthetic Aperture Radar

ASF Alaska Satellite Facility

ASHOE Airborne Southern Hemisphere Ozone Experiment

ASPI Alcatel Space Industries

ASTER Advanced Spaceborne Thermal Emission and Reflection Radiometer

ASTEX Atlantic Stratocumulus Transition Experiment

ATBD	Algorithm Theoretical Basis Document
ATI	Advanced Technology Initiative
ATLAS	Atmospheric Laboratory for Applications and Science
ATM	Airborne Topographic Mapper
ATMOS	Atmospheric Trace Molecule Spectroscopy Experiment
ATMS	Advanced Technology Microwave Sounder
ATOVS	Advanced TOVS
ATS	Applications Technology Satellite
ATSR	Along Track Scanning Radiometer
AVG	Average (used for the CERES Monthly Regional Radiative Fluxes and Clouds data product)
AVHRR	Advanced Very High Resolution Radiometer
AVIRIS	Airborne Visible/Infrared Imaging Spectrometer
AWARDS	Agricultural Water Resources and Decision Support
AWIN	Aviation Weather Information Network

B

BASINS	Better Assessment Science Integrating Point and Non-point Sources
BATC	Ball Aerospace & Technologies Corp.
BOREAS	Boreal Ecosystems-Atmosphere Study
bps	bits per second
BRDF	Bidirectional Reflectance Distribution Function
BSRN	Baseline Surface Radiation Network
BUV	Backscatter Ultraviolet

C

CAAG	CloudSat Applications Advisory Group
CADRE	Crop Assessment Data Retrieval and Evaluation
CAGEX	CERES/ARM/GEWEX Experiment
CALIOP	Cloud-Aerosol Lidar with Orthogonal Polarization
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations
CaPE	Convection and Precipitation/ Electrification field project
CC	Cloud Camera
CCAD	Comision CentroAmericana de Ambiente y Desarrollo (Central American Commission for Environment and Development)
CCD	Charge-Coupled Device
CCN	Cloud Condensation Nuclei
CCRI	Climate Change Research Initiative
CCSDS	Consultative Committee for Space Data Systems
CCSP	Climate Change Science Program (U.S.)
CCTP	Climate Change Technology Program (U.S)
CDC	Centers for Disease Control
CDR	Critical Design Review
CEES	Committee on Earth and Environmental Sciences
CENR	Committee on Environment and Natural Resources
CEOS	Committee on Earth Observation Satellites
CEP	Center for Environment Prediction
CERES	Clouds and the Earth's Radiant Energy System
CFC	Chlorofluorocarbon
CHAMP	Challenging Minisatellite Payload
CHIPS	Cosmic Hot Interstellar Plasma Spectrometer
CINDI	Center for Integration of National Disaster Information
CIRA	Cooperative Institute for Research in the Atmosphere (Colorado State University)
CLAES	Cryogenic Limb Array Etalon Spectrometer
CLAMS	Chesapeake Lighthouse and Aircraft Measurements for Satellites

CLASS	Comprehensive Large Array data Stewardship System
CLIVAR	CLImate VARiability and Prediction
CLPX	Cold Land Processes Experiment
CMAQ	Community Multiscale Air Quality modeling system
CMDL	Climate Monitoring and Diagnostics Laboratory (NOAA)
CMIS	Conical Scanning Microwave Imager/ Sounder
CNES	Centre National d'Etudes Spatiales (France)
CO	carbon monoxide
CODMAC	Committee on Data Management, Archiving, and Computing
CONAE	Comision Nacional de Actividades Espaciales (Argentina)
COSEPUP	Committee on Science, Engineering, and Public Policy
CoSMIR	Conical Scanning Millimeter-wave Imaging Radiometer
COVE	CERES Ocean Validation Experiment
CPL	Cloud Physics Lidar
CPR	Cloud Profiling Radar
CPTEC	Centro de Previsão de Tempo e Estudos Climáticos (Center for Weather and Climate Prediction) (Brazil)
CQUEST	Carbon Query and Evaluation Support Tools
CrIMSS	Cross-track Infrared Microwave Sounding Suite (CrIS and ATMS)
CrIS	Cross-track Infrared Sounder
CRS	Cloud Radar System
CRYSTAL-FACE	Cirrus Regional Study of Tropical Anvils and Cirrus Layers – Florida Area Cirrus Experiment
CSA	Canadian Space Agency
CSIRO	Commonwealth Scientific and Industrial Research Organization
CSP	Common Signal Processor
CU	University of Colorado
CZCS	Coastal Zone Color Scanner

D

DA	Data analysis
DAAC	Distributed Active Archive Center
DAO	Data Assimilation Office
DAR	Data Acquisition Request
DAS	Data Assimilation System
DB	Direct Broadcast
DCS	Data Collection System
DEM	Digital Elevation Model
DFA	Dual-Frequency Radar Altimeter
DHS	Department of Homeland Security
DIDM	Digital Ion Drift Meter
DLR	Deutsches Zentrum für Luft-und Raumfahrt
DMSP	Defense Meteorological Satellite Program
DMWG	Data Management Working Group
DOC	Department of Commerce
DoD	Department of Defense
DOE	Department of Energy
DOI	Department of the Interior
DORIS	Doppler Orbitography and Radiopositioning Integrated by Satellite
DOS	Department of State
DOT	Department of Transportation
DPR	Dual-frequency Precipitation Radar
DRTS	Data Relay Test Satellite
DTU	Danmarks Tekniske Universitet (Technical University of Denmark)
DU	Dobson Unit
DWL	Doppler Wind Lidar

E

EASOE	European Arctic Stratospheric Ozone Experiment
ECHO	EOS Clearing House
ECMWF	European Centre for Medium-Range Weather Forecasts

ECS EOSDIS Core System

EDC EROS Data Center

EDG EOS Data Gateway

EDOS EOS Data and Operations System

EDR Environmental Data Records

EDS Expedited Data Sets

ed., eds. Editor, editors

EGPM European GPM

EGS ESE Ground Systems

EIK Extended Interaction Klystron

ELV Expendable Launch Vehicle

EMOS EOS Mission Operations System

EMSn EOS Mission Support network

ENSO El Niño-Southern Oscillation

Envisat Environmental Satellite (ESA)

EO-1 Earth Observing-1

EOC *Alternatively:* Earth Observation Center (Japan); EOS Operations Center

EORC Earth Observation Research and application Center (JAXA)

EOS Earth Observing System

EOSDIS EOS Data and Information System

EOSP Earth Observing Scanning Polarimeter

EOSPSO EOS Project Science Office

EP Earth Probe

EPA Environmental Protection Agency

EPHTN Environmental Public Health Tracking Network

EPIC Energetic Particles and Ion Composition

ER-2 A NASA high-altitude research aircraft (modified Lockheed U-2)

ERB Earth Radiation Budget

ERBE Earth Radiation Budget Experiment

ERBS Earth Radiation Budget Satellite

ERCN Educator Resource Center Network

EROS Earth Resources Observation System

ERPS EOS Real Time Processing System

ERS European Remote Sensing Satellite

ERTS Earth Resources Technology Satellite

ESA European Space Agency

ESDIS Earth Science Data and Information System

ESE Earth Science Enterprise (NASA)

ESIP Earth Science Information Partner

ESMF Earth System Modeling Framework

ESMO Earth Science Mission Operations

ESMR Electrically Scanning Microwave Radiometer

ESR *Alternatively:* Earth and Space Research; Electrical Substitution Radiometer

ESRIN European Space Research Institute (ESA)

ESSAAC Earth System Science and Applications Advisory Committee

ESSC Earth System Sciences Committee

ESSn EOS Science Support network

ESSP Earth System Science Pathfinder (NASA)

ESTAR Electronically Steered Thinned Array Radiometer

ESTO Earth Science Technology Office

ETM Enhanced Thematic Mapper

ETM+ Enhanced Thematic Mapper Plus

EU European Union

EUMETSAT European Organisation for the Exploitation of Meteorological Satellites

EUV Extreme ultraviolet radiation

EVI Enhanced Vegetation Index (MODIS)

F

FAA Federal Aviation Administration

FEMA Federal Emergency Management Agency

FGM Fluxgate Magnetometer

FIFE First ISLSCP Field Experiment

FIRE First ISCCP Regional Experiment

FMI Finnish Meteorological Institute

FOO	Flight Of Opportunity
FOS	Flight Operations Segment
FOV	Field of View
FPAR	Fraction of Photosynthetically Active Radiation
FSA	Federal Space Agency of Russia
FSSP	Forward Scattering Spectrometer Probe
FTS	Fourier Transform Spectrometer
FWHM	Full width half maximum

G

GAIM	Global Analysis, Interpretation, and Modeling
GAME	GEWEX Asian Monsoon Experiment
GAME-T	GEWEX Asian Monsoon Experiment-Tropics
Gbits	Gigabits
GCMD	Global Change Master Directory
GCIP	GEWEX Continental-Scale International Project
GCM	General Circulation Model (also Global Climate Model)
GCOS	Global Climate Observing System
GDAAC	Goddard Earth Sciences Distributed Active Archive Center
GDR	Geophysical Data Record
GEBA	Global Energy Balance Archive
GEO	Group on Earth Observations
GEOCOMP	GEOcoding and COMPositing System
GEOS	Goddard Earth Observing System
GEOSS	Global Earth Observation System of Systems
GERB	Geostationary Earth Radiation Budget
GES	Goddard Earth Sciences
GEWEX	Global Energy and Water Cycle Experiment
GFDL	Geophysical Fluid Dynamics Laboratory (NOAA)
GFZ	GeoForschungsZentrum Potsdam (Germany's National Research Centre for Geosciences)
GHCN	Global Historical Climatology Network
GHRC	Global Hydrology Resource Center
GIS	Geographic Information System
GISS	Goddard Institute for Space Studies
GLAS	Geoscience Laser Altimeter System
GLCTS	Global Landcover Test Site initiative
GLI	Global Imager
GLIMS	Global Land Ice Monitoring from Space
GLIS	Global Land Information System
GloVis	Global Visualization Viewer
GMI	GPM Microwave Imager
GMS	Geostationary Meteorological Satellite
GOALS	Global Ocean-Atmosphere-Land System
GOES	Geostationary Operational Environmental Satellite
GOLPE	GPS Occultation and Passive Reflection Experiment
GOME	Global Ozone Monitoring Experiment
GOMOS	Global Ozone Monitoring By Occultation of Stars
GPCP	Global Precipitation Climatology Project
GPM	Global Precipitation Measurement mission
GPS	Global Positioning System
GPS-DR	Global Positioning System Demonstration Receiver
GPS-TR	Global Positioning System TurboRogue
GPSOS	Global Positioning Sensor Occultation System
GRACE	Gravity Recovery And Climate Experiment
GRDC	Global Runoff Data Center
GSFC	Goddard Space Flight Center
GSOC	German Space Operations Center
GTOS	Global Terrestrial Observing System
GV	Ground Validation
GVaP	GEWEX Water Vapor Project

H

HAB Harmful Algae Bloom

HAIRS High Accuracy Inter-satellite Ranging System

HALOE Halogen Occultation Experiment

HAZUS Hazards U.S.

HCS High Sensitivity Camera [Argentina's Comision Nacional de Actividades Especiales (National Commission of Special Activities)]

HDF Hierarchical Data Format

HEIFE Heihe river basin Field Experiment

HHS Health and Human Services

HIRAM HIRDLS Radiometric Model

HIRDLS High Resolution Dynamics Limb Sounder

HIRS High Resolution Infrared Radiation Sounder

HPA High Power Amplifier

H Pol Horizontal polarization

HRDI High Resolution Doppler Imager

hres Horizontal resolution

HRTC High Resolution Technological Camera

HSB Humidity Sounder for Brazil

HSI Hyperspectral Imager

HUBEX Huaihe River Basin Experiment

Hydros Hydrosphere State Mission

Hyperion A hyperspectral instrument

I

IABP International Arctic Buoy Program

IAS Image Assessment System

IASI Infrared Atmospheric Sounding Interferometer

IAVCEI International Association of Volcanology and Chemistry of the Earth's Interior

ICARE Influence of Space Radiation on Advanced Components

ICESat Ice, Clouds, and Land Elevation Satellite

ICRCCM Intercomparison of Radiation Codes for Climate Models

ICSU International Council of Scientific Unions

IDPS Interface Data Processing Segment (NPOESS)

IDS Interdisciplinary Science investigation (EOS)

IELV Intermediate Expendable Launch Vehicle

IEOS International Earth Observing System

IFOV Instantaneous Field of View

IGAC International Global Atmospheric Chemistry

IGBP International Geosphere-Biosphere Programme

IGDR Interim Geophysical Data Records

IGOS Integrated Global Observing Strategy

IGPPDI Global Primary Production Data Initiative

IHP International Hydrological Program

IIP Instrument Incubator Program

IIR Imaging Infrared Radiometer

ILAS Improved Limb Atmospheric Spectrometer

IMAS Integrated Multispectral Atmospheric Sounder

IMS Information Management System

INDOEX Indian Ocean Experiment

INES Italian Navigation Experiment

INPE Instituto Nacional de Pesquisas Espaciais (Brazil)

InSAR Interferometric Synthetic Aperture Radar

IOC Intergovernmental Oceanographic Commission

IP Internet Protocol

IPCC Intergovernmental Panel on Climate Change

IPO Integrated Program Office

IR Infrared

IRS-P3 Indian Remote Sensing Satellite P3

ISAMS Improved Stratospheric and Mesospheric Sounder

ISCCP International Satellite Cloud Climatology Project

ISDC Information System and Data Center (GFZ)

ISFS Invasive Species Forecasting System

ISLSCP International Satellite Land Surface Climatology Project

IST *Alternatively:* Instrument Star Tracker, Instrument Support Terminals, Italian Star Tracker

ITCZ Inter-Tropical Convergence Zone

ITOVS International TIROS Operational Vertical Sounder

IWG Investigators Working Group (EOS)

IWGEO U.S. Interagency Working Group on Earth Observations

J

JAXA Japan Aerospace Exploration Agency

JERS Japanese Earth Remote-Sensing Satellite

JGOFS Joint Global Ocean Flux Study

JMR Jason-1 Microwave Radiometer

JORNEX Jornada Experiment

JPL Jet Propulsion Laboratory

K

kpbs kilobits per second

KBR K-Band ranging instrument assembly

KNMI Koninklijk Nederlands Meteorologisch Instituut (Royal Netherlands Meteorological Institute)

L

LAC *Alternatively:* LEISA Atmospheric Corrector; Local Area Coverage

LAGEOS Laser Geodynamics Satellite

LAI Leaf-Area Index

Landsat Land Remote-Sensing Satellite

LaRC Langley Research Center

LAS Limb Atmospheric Spectrometer

LASP Laboratory for Atmospheric and Space Physics (U. of Colorado)

LBA Large Scale Biosphere-Atmosphere Experiment in Amazonia

LBR L-Band Radiometer

LBS L-Band Scatterometer

LDCM Landsat Data Continuity Mission

LED Light Emitting Diode

LEISA Linear Etalon Imaging Spectral Array

LEO Low Earth Orbit

LIMS Limb Infrared Monitor of the Stratosphere

LIS Lightning Imaging Sensor

LITE Lidar In-space Technology Experiment

LL Lincoln Laboratory

LLNL Lawrence Livermore National Laboratory

LORE Limb Ozone Retrieval Experiment

LP Land Processes

LPA Laser Profile Array

LPGS Level 1 Product Generation System

LRA Laser Retroreflector Array

LRIR Limb Radiance Inversion Radiometer

LRR Laser Retro Reflector

LRS Laser Reference System

LST Land Surface Temperature

LW Longwave

M

MAP Microwave Anisotropy Probe

MAPS Measurement of Air Pollution from Satellites

MAS MODIS Airborne Simulator

MAX Mid-Atlantic Crossroads

MBLA Multi-Beam Laser Altimeter

Mbps Megabits per second

MERIS Medium-Resolution Imaging Spectrometer

METI Ministry of Economy, Trade and Industry (Japan)

METOP Meteorological Operational Satellite (EUMETSAT)

MFOV Medium Field of View

MGS McMurdo Ground Station

MHS Microwave Humidity Sounder

MIMR Multifrequency Imaging Microwave Radiometer

MIR Millimeter-wave Imaging Radiometer

MISR Multi-angle Imaging SpectroRadiometer

MIT Massachusetts Institute of Technology

MITI Ministry of International Trade and Industry (Japan)

MLS Microwave Limb Sounder

MMIC Microwave Monolithic Integrated Circuit

MMP Magnetic Mapping Payload

MMRS Multi-Spectral Medium Resolution Scanner

MMS Malaria Modeling and Surveillance

MO Mission Operations

MOC Mission Operations Center

MODIS Moderate Resolution Imaging Spectroradiometer

MODLAND MODIS Land

MOLA Mars Orbiter Laser Altimeter

MOPITT Measurements of Pollution in the Troposphere

MOS Modular Optoelectronic Scanner

MOU Memorandum of Understanding

MOZART Model for Ozone And Related Chemical Tracers

MSFC Marshall Space Flight Center

MSMT Mission & Science Measurement Technology

MSS Multispectral Scanner

MSSCC Multicolor Spin Scan Cloud Camera

MSU Microwave Sounding Unit

MTPE Mission to Planet Earth

MVI MODIS Vegetation Index

N

NAO North Atlantic Oscillation

NAS *Alternatively:* National Airspace System; National Academy of Sciences

NASA National Aeronautics and Space Administration

NASDA National Space Development Agency (Japan)

NAST NPOESS Airborne Sounder Testbed

NBIOME Northern Biosphere Observation and Modeling Experiment

NCAR National Center for Atmospheric Research

NCDC National Climatic Data Center

NCEP National Centers for Environmental Prediction

NDSC Network for Detection of Stratospheric Change

NDVI Normalized Difference Vegetation Index

NEΔT Noise Equivalent Delta Temperature

NESDIS National Environmental Satellite, Data, and Information Service

NEXRAD Next Generation Weather Radar

NGO Non-Governmental Organization

NGST Northrop Grumman Space Technology

NIAC NASA Institute for Advanced Concepts

NIH National Institutes of Health

NIMA	National Imagery and Mapping Agency
NIP	New Investigator Program
NIR	Near-Infrared
NISN	NASA Integrated Services Network
NIST	National Institute of Standards and Technology
NIVR	Nederlands Instituut voor Vliegtuigontwikkeling en Ruimtevaart
NLAPS	National Land Archive Production System
NMC	National Meteorological Center
NMP	New Millennium Program
NOAA	National Oceanic and Atmospheric Administration
NOPEX	Northern Hemisphere Climate-Processes Land-Surface Experiment
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPP	NPOESS Preparatory Project
NRA	*Alternatively:* NASA Radar Altimeter; NASA Research Announcement
NRC	National Research Council
NRCAN	Natural Resources Canada
NREN	NASA Research and Education Network
NSCAT	NASA Scatterometer
NSF	National Science Foundation
NSIDC	National Snow and Ice Data Center
NSTC	National Science and Technology Council
NWP	Numerical Weather Prediction

O

OClO	Chlorine Dioxide
OCMIP	Ocean Carbon-cycle Model Intercomparison Project
OCO	Orbiting Carbon Observatory
OCPP	Orbital Cloud Photopolarimeter Instrument
OCTS	Ocean Color and Temperature Scanner
ODB	Orbit Determination Beacon
OGDR	Operational Geophysics Data Record
OLR	Outgoing Longwave Radiation
OLS	Operational Linescan System
OMB	Office of Management and Budget
OMI	Ozone Monitoring Instrument
OMPS	Ozone Mapping and Profiler Suite
ONERA	Office National d'Etudes et de Recherches Aerospatiale (France)
ONR	Office of Naval Research
OPS	Optical Sensor
ORNL	Oak Ridge National Laboratory
OSC	Orbital Sciences Corporation
OSIRIS	Optical System for Imaging and Low Resolution Integrated Spectroscopy
OSTM	Ocean Surface Topography Mission
OSTP	Office of Science and Technology Policy
OSU	Oregon State University
OV	OrbView (OSC)
OVM	Overhauser Magnetometer

P

PABSI	Profiling A-Band Spectrometer/Visible Imager
PALS	Passive and Active L and S Band System
PAR	Photosynthetically Active Radiation
PARASOL	Polarization and Anisotropy of Reflectances for Atmospheric Sciences coupled with Observations from a Lidar
PARCA	Program for Arctic Regional Climate Assessment
PC	Power Control
PDF	Portable Document Format
PDS	Production Data Sets
PEM	Particle Environmental Monitor
PI	Principal Investigator
PICASSO	Pathfinder Instruments for Cloud and Aerosol Spaceborne Observations

PILPS	Project for Intercomparison of Land-Surface Parameterization Schemes
PIP	Premium Internet Protocol
PMR	Pressure Modulator Radiometer
PMW	Passive Microwave
PNNL	Pacific Northwest National Laboratory
PO.DAAC	Physical Oceanography Distributed Active Archive Center (JPL)
POD	Precise Orbit Determination
POE	Precise Orbit Ephemeris
POES	Polar-orbiting Operational Environmental Satellite
POESS	Polar-orbiting Operational Environmental Satellite System
POLDER	Polarization and Directionality of the Earth's Reflectances
PoleScat	Polarimetric Scatterometer
ppm	parts per million
PPS	Precipitation Processing System
PR	Precipitation Radar
PSO	Project Science Office
PSR	*Alternatively:* Polarimetric Scanning Radiometer; Pre-Ship Review
PSU	Practical Salinity Unit
PW	Precipitable Water
PWV	Precipitable Water Vapor

Q

QBO	Quasi-Biennial Oscillation
QOTL	Quasi-Optical Transmission Line
QuikSCAT	Quick Scatterometer

R

RAC	Regional Applications Center
RACMO	Regional Atmospheric Climate Model
RADARSAT	Radar Satellite (Canada)
RAM	Random Access Memory
RAMS	Regional Atmospheric Modeling System
RASA	Russian Aviation and Space Agency
RDC	Raw Data Center (DLR)
RDR	Raw Data Record
REASoN	Research, Education, and Applications Solutions Network
RESAC	Regional Earth Science Applications Center
RET Screen	Renewable Energy Technology Screen
RF	Radio Frequency
RFP	Request for Proposal
RFU	Radio Frequency Unit
RGPS	RADARSAT Geophysical Processor System
RMS	Root Mean Square
RPM	Revolutions per minute
RSP	Research Scanning Polarimeter

S

SAC-C	Satelite de Aplicaciones Cientificas-C (Argentina)
SAC-D	Aquarius/Satelite de Aplicaciones Cientificas-D
SADCO	South African Data Center for Oceanography
SAFARI	Southern African Regional Science Initiative
SAGE	Stratospheric Aerosol and Gas Experiment
SAM	Stratospheric Aerosol Measurement
SAMS	Stratospheric and Mesospheric Sounder
SAR	Synthetic Aperture Radar
SBIR	Small Business Innovative Research
SBUV	Solar Backscatter Ultraviolet
SCA	Star Camera Assembly
SCANSAR	Scanning Synthetic Aperture Radar
SCAR-B	Smoke, Clouds, and Radiation-Brazil
SCF	Scientific Computing Facility

SCIAMACHY	Scanning Imaging Absorption Spectrometer for Atmospheric Chartography
SCISAT	Science Satellite (Canada)
SCISSAP	Southern Center for the Integrated Study of Secondary Air Pollutants
SCOPE	Scientific Committee on Problems of the Environment
SCRIBE	Stratospheric Cryogenic Infrared Balloon Experiment
SDP	Standard Data Product
SDPS	Science Data Processing Segment
SDR	Sensor Data Record
SDS	Scientific Data Set
SeaWiFS Sensor	Sea-viewing Wide Field-of-view
SEDAC	Socioeconomic Data and Applications Center
SEE	Solar EUV Experiment
SEEDS	Strategic Evolution of ESE Data Systems
SESAME	*Alternatively:* Severe Environmental Storms and Mesoscale Experiment; Second European Stratospheric Arctic and Mid-Latitude Experiment
SGS	Svalbard Ground Station
SHEBA	Surface Heat Budget of the Arctic Ocean
SHIS	Scanning High Resolution Interferometer Sounder
SHM	Scalar Helium Magnetometer
SI	*Alternatively:* Smithsonian Institution; Systeme Internationale (International System of Units)
SIM	Spectral Irradiance Monitor
SIMBIOS	Sensor Intercomparison and Merger for Biological and Interdisciplinary Oceanic Studies
SIMIP	Sea Ice Model Intercomparison Project
SIP	*Alternatively:* Standard Internet Protocol; Science Implementation Plan (GPM)
SIPS	Science Investigator-led Processing System
SIR	Shuttle Imaging Radar
SIR-C	Shuttle Imaging Radar-C
SIRAL	Synthetic Aperture Interferometric Radar Altimeter
SLA	Shuttle Laser Altimeter
SLC	Scan Line Corrector
SLFMR	Scanning Low Frequency Microwave Radiometer
SLR	Satellite Laser Ranging
SMEX	Soil Moisture Experiment
SMM	Solar Maximum Mission
SMMR	Scanning Multichannel Microwave Radiometer
SNOE	Student Nitric Oxide Explorer
SOC	Science Operations Center
SOHO	Solar Heliospheric Observatory
SOLAS	Surface Ocean Lower Atmosphere Study
SOLCON	Solar Constant (Belgium)
SOLSE	Shuttle Ozone Limb Sounding Experiment
SOLSTICE	Solar Stellar Irradiance Comparison Experiment
SORCE	Solar Radiation and Climate Experiment
SOS	Southern Oxidants Study
SPCZ	South Pacific Convergence Zone
SPOT	Systeme pour l'Observation de la Terre
SRB	Surface Radiation Budget
SRBEX	Susquehanna River Basin Experiment
SRS	Stellar Reference System
SRTM	Shuttle Radar Topography Mission
SSA	SuperStar Accelerometer
SSALT	Solid State Radar Altimeter
SSBUV	Shuttle Solar Backscatter Ultraviolet
SSCC	Spin Scan Cloud Camera
SSFR	Solar Spectral Flux Radiometer
SSHA	Sea Surface Height Anomaly
SSI	Solar Spectral Irradiance
SSM/I	Special Sensor Microwave/Imager

SSMI/S	Special Sensor Microwave Imager/ Sounder
SSR	Solid State Recorder
SSS	Sea Surface Salinity
SST	Sea Surface Temperature
SSU	Stratospheric Sounding Unit
STEM	Science, Technology, Engineering and Mathematics
SURF-III	Synchrotron Ultraviolet Radiation Facility III (NIST)
SUSIM	Solar Ultraviolet Spectral Irradiance Monitor
SVAT	Soil-Vegetation-Atmosphere Transfer model
SVS	Synthetic Vision System
SW	Shortwave
SWG	Science Working Group
SWIR	Shortwave Infrared
SXP	Solar XUV Photometer
SZA	Solar Zenith Angle

T

TAMMS	Turbulent Air Motion Measurement System
TARFOX	Tropospheric Aerosol Radiative Forcing Observational Experiment
TCP/IP	Transmission Control Protocol/Internet Protocol
TDRSS	Tracking and Data Relay Satellite System
TES	Tropospheric Emission Spectrometer
THESEO	Third European Stratospheric Experiment on Ozone
TIM	Total Irradiance Monitor
TIMED	Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics
TIR	Thermal Infrared
TIROS	Television and Infrared Observation Satellite
TL	Team Leader
TM	*Alternatively:* Thematic Mapper; Team Member
TMI	TRMM Microwave Imager
TMR	TOPEX Microwave Radiometer
TOA	Top Of the Atmosphere
TOGA	Tropical Ocean Global Atmosphere
TOMS	Total Ozone Mapping Spectrometer
TOPEX	TOPography Experiment for ocean circulation
TOPSAR	Topographic Synthetic Aperture Radar
TOVS	TIROS Operational Vertical Sounder
TRACE-A	Transport and Chemistry near the Equator over the Atlantic
TRAGNET	Trace Gas Network (United States)
TRCN	Teacher Resource Center Network
TRMM	Tropical Rainfall Measuring Mission
TRSR	Turbo Rogue Space Receiver
TSDIS	TRMM Science Data and Information System
TSI	Total Solar Irradiance

U

U	University
UARS	Upper Atmosphere Research Satellite
UCAID	University Corporation for Advanced Internetworking Development
U.K.	United Kingdom
UKMO	United Kingdom Meteorological Office
UMCP	University of Maryland, College Park
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
U.S.	United States
USAF	U.S. Air Force
USAID	U.S. Agency for International Development
USBoR	U.S. Bureau of Reclamation
USDA	U.S. Department of Agriculture

USGCRP U.S. Global Change Research Program

USGS U.S. Geological Survey

USO Ultra Stable Oscillator

USRA University Space Research Association

USWRP U.S. Weather Research Program

UTCSR University of Texas Center for Space Research

UV Ultraviolet radiation

V

VAFB Vandenberg Air Force Base

VCL Vegetation Canopy Lidar

VEMAP Vegetation/Ecosystem Modeling and Analysis Project

VHRR Very High Resolution Radiometer

VI Vegetation Index

VIIRS Visible Infrared Imaging Radiometer Suite

VIRGO Variability of Solar Irradiance and Gravity Oscillations

VIRS Visible and Infrared Scanner

VIS Visible; sometimes visible/near-infrared

VIS/IR Visible/Infrared

VLBI Very Long Baseline Interferometry

VNIR Visible and Near Infrared

VOS Volunteer Observing Ship

V Pol Vertical Polarization

vres Vertical resolution

W

WARP Wideband Advanced Recorder Processer

WCRP World Climate Research Programme

WFC Wide-Field Camera

WFOV Wide Field of View

WGS Wallops Flight Facility Ground Station

WINDII Wind Imaging Interferometer

WIST Warehouse Inventory Search Tool

WMO World Meteorological Organization

WOCE World Ocean Circulation Experiment

WRS Worldwide Reference System

WSC White Sands Complex

WSMC Western Space and Missile Center

WSR Weather Surveillance Radar

WVR Water Vapor Radiometer

X

X-SAR X-Band Synthetic Aperture Radar

XPS XUV Photometer System

XUV Solar Soft X-ray

Z

ZAVG Zonal Average (used for the CERES Monthly Zonal and Global Radiative Fluxes and Clouds data product)

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