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Editor's Corner

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As it has done for nearly sixty years, NASA continues to push technology to enable new science. In 2014 NASA's Science Mission Directorate's (SMD) Advanced Technology Initiatives Program (ATIP) and the Earth Science Technology Office's (ESTO) In-Space Validation of Earth Science Technologies (InVEST) program selected the IceCube project, a fast-track spaceflight demonstration of an 883-GHz cloud radiometer on a *3U CubeSat*.¹ The primary objective of IceCube is to raise the technology readiness level of the 883-GHz IceCube Cloud-Ice Radiometer (ICIR) for future Earth science missions² by flying a commercial receiver in spaceflight demonstration. This is a high-risk "pathfinder" mission designed and built using commercial off-the-shelf components, but with the potential for great reward in testing a new measurement concept.

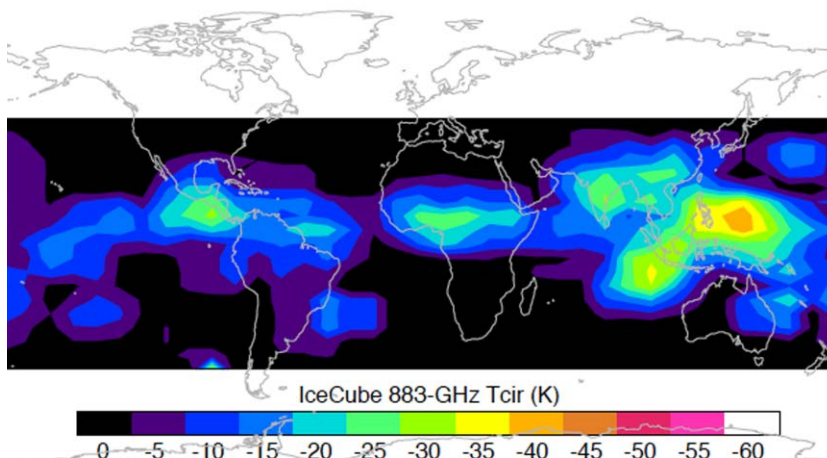
After a 2.5-year development, IceCube launched to the ISS on April 19, 2017 through a rideshare with the Orbital Sciences Commercial Resupply Services Flight 7 (OA-7) resupply mission, and successfully deployed from the ISS on May 16, 2017. First-light measurements from ICIR were obtained on June 6 with a regular *technology-demonstration* mode starting on June 16 for daytime-only observations. The first 883-GHz cloud radiance map from IceCube (shown below) covers the period from June 20 through July 2. As of this writing, IceCube continues to operate normally with the CubeSat spinning around the sun vector in daytime. The spin produces periodical views between Earth and space, allowing radiometric calibration of ICIR.

IceCube was launched through NASA's CubeSat Launch initiative (CSLI), which provides access to space for small satellites developed by NASA Centers and programs, educational institutions, and non-profit organizations giving CubeSat developers access to a low-cost pathway to conduct research in the areas of science,

continued on page 2

¹ CubeSats are a class of miniature research spacecraft called nanosatellites. They are typically measured in *units* (U), where 1U is defined as a volume of about 10 cm x 10 cm x 10 cm (~4 in x 4 in x 4 in), and typically weigh less than 1.33 kg. IceCube is thus designated as a *3U CubeSat*.

² Clouds play an extremely important role in regulating Earth's climate, and yet they remain one of the greatest sources of uncertainty in current climate models. Submillimeter (submm) wave remote sensing has been shown to have the capability of penetrating clouds and measuring ice mass and microphysical properties. The 883-GHz frequency is a spectral window whereby the radiation is highly sensitive to ice cloud scattering and interacts in depth with volume ice mass inside the cloud.



The first map of 883-GHz cloud-induced radiance (T_{cir}) from the IceCube Cloud-Ice Radiometer (ICIR). T_{cir} is defined as the difference between observed and modeled clear-sky radiances, and it is roughly proportional to cloud ice amount above ~11 km. (T_{cir} is negative because cloud scattering acts to reduce the upwelling radiation at submm-wave frequencies.) **Image credit:** NASA's ICECube team

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Reminder: To view newsletter images in color, visit
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exploration, technology development, education, or operations. The initiative is an integrated cross-agency collaborative effort led by NASA's Human Exploration and Operations Mission Directorate to streamline and prioritize ride share and deployment opportunities of CubeSats.

To date, NASA has selected 152 CubeSat missions from 85 unique organizations representing 38 states and the District of Columbia. In addition to IceCube, several other current or planned CubeSat missions are testing technology and/or studying subjects that may have applications for Earth Science. In November 2016, for example, the Radiometer Assessment using Vertically Aligned Nanotubes (RAVAN) CubeSat was launched from Vandenberg Air Force Base, collecting "first light" on January 25 of this year. RAVAN, a project led by the Johns Hopkins Applied Physics Laboratory measures outgoing radiative energy. Several other CubeSats are planned for launch over the coming year. The Microwave Radiometer Technology Acceleration mission (MiRaTA) will be carried into space onboard NOAA's Joint Polar Satellite System-1 (JPSS-1) satellite (scheduled to launch later this year) to collect data on temperature, water vapor, and cloud ice. The Hyper-Angular Rainbow Polarimeter (HARP), scheduled to launch to the ISS in January 2018, will retrieve aerosol and cloud particle properties using multiangle polarimetric measurements. Two larger 6U CubeSats will launch to the ISS in March 2018: RainCube, which will measure precipitation, will be the first

active-remote-sensing radar on on CubeSat platform (K_a-band); and CubeRRT will demonstrate wideband radio frequency interference (RFI) mitigating backend technologies vital for future space-borne microwave radiometers. Similar to IceCube, these CubeSat missions are all part of the InVEST program.

In addition, the Temporal Experiment for Storms and Tropical Systems Technology Demonstration (TEMPEST-D) is another 6U CubeSat that will launch in March 2018, as part of the Earth Venture Technology initiative.

The Total Solar Irradiance Sensor-1 (TSIS-1) mission passed its pre-shipment review (PSR) on July 20, 2017. Its two instruments—the Total Irradiance Monitor (TIM) and the Spectral Irradiance Monitor (SIM)—are now at KSC. The launch date remains NET November 1 on SpaceX Commercial Resupply Service-13. The TSIS-1 mission will provide absolute measurements of the total solar irradiance (TSI) and spectral solar irradiance (SSI), important for accurate scientific models of climate change and solar variability. TSIS-1 will continue the 35-year data record of TSI measurements that is currently being maintained by the TIM instrument on the aging Solar Radiation and Climate Experiment (SORCE) spacecraft (launched in 2003) and augmented (since 2013) by the Total Solar Irradiance Calibration Transfer Experiment (TCTE) instrument, a joint mission with NOAA and the U.S. Air Force.

The ECOSystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) passed its Environmental Test Readiness Review (ETRR) and Safety Phase III Review, and final integration has begun. Delivery to KSC is anticipated to take place in August 2017 where it will be held in storage until its planned April 2018 launch. ECOSTRESS will measure the temperature of plants from the ISS and use that information to better understand their water needs and responses to heat and water stress. The instrument is currently being built at JPL. The third ECOSTRESS Science Team Meeting took place May 15-17, 2017, at the University of California, Davis, and was an opportunity for the team to review mission science specifications, milestones, and schedules, and to discuss progress towards these goals. Turn to page 24 of this issue to learn more about the status of ECOSTRESS.

The Global Ecosystem Dynamics Investigation (GEDI) continues to meet its milestones as it moves towards a scheduled December 2018 launch. Engineering model hardware fabrication and key interface testing are wrapping up, flight-model fabrication is fully underway, integration and test facilities are ready, and the Ground System and Mission Operations Center are in preparation. GEDI is a multibeam lidar that will provide Earth's first comprehensive and high-resolution dataset of ecosystem structure. Development of the GEDI laser is also progressing well; sensor performance remains solid with good margins. An earlier issue that was causing the beam to exhibit laser side-lobes has been resolved and the laser now exhibits Gaussian spatial beam quality.³ The third GEDI Science Definition Team (SDT) meeting took place April 4-6, 2017, in Annapolis, MD; turn to page 28 to learn more.

In other news, the Ocean Surface Topography Mission (OSTM)/Jason-2 satellite (a partnership among NASA, NOAA, CNES, and EUMETSAT) recently marked the ninth anniversary of its launch—well exceeding its planned three-to-five-year mission. During that time, OSTM/Jason-2 has precisely measured the height of 95% of the world's ice-free ocean every 10 days. Since October 2016, it has operated in a *tandem mission* with its successor, Jason-3, launched in January 2016, doubling coverage of the global ocean and improving data resolution for both missions.

Along with Jason-3, OSTM/Jason-2 contributes to a satellite ocean altimetry data record that began with the launch of the U.S./French Ocean Topography Experiment (Topex)/Poseidon satellite in 1992. Although OSTM/Jason-2 continues to perform well, onboard systems have aged and the harsh environment

³ GEDI's laser footprint energy follows a two-dimensional Gaussian distribution, exhibiting stronger power in the center and fading towards the edges. The nominal footprint size (22 m) indicates the diameter within which 86% of the energy is contained.

of space has begun to take a toll on key satellite components. It was therefore decided to move the older satellite out of its current shared orbit with Jason-3 in order to safeguard the orbit for Jason-3 and its planned successor, Jason-Continuity of Service (CS)/Sentinel-6,⁴ planned for launch in 2020. On June 20 (the ninth anniversary of launch) Jason-2's four mission partner agencies agreed to lower Jason-2's orbit by 27 km (to 1309 km) providing a repeat orbit period of just more than one year. Final orbit transfer activities were completed on July 10. This *long-repeat orbit* will allow OSTM/Jason-2 to collect data along a series of very closely spaced ground tracks just 8 km apart. The result will be a new, high-resolution estimate of Earth's average sea surface height. The data obtained will also help prepare for the next generation of global satellite altimetry missions, including the NASA/CNES/CSA/UKSA Surface Water and Ocean Topography (SWOT) mission, planned for launch in 2021; and Sentinel-3B, to be launched in early 2018.

Finally, the third A-Train Symposium took place April 19-21, 2017, in Pasadena, CA. *The Earth Observer* has been reporting regularly on the accomplishments of individual instruments flying on A-Train Constellation member satellites. However, the value of the Constellation is in the synergistic use of multi-instrument observations. It was clear from the many presentations that the A-Train transformed the way we study and understand the Earth's interrelated geophysical systems. An overarching theme of the symposium was the use of A-Train data to validate and improve climate models. Clouds, aerosols, and their interactions were the dominant symposium topics. Other topics included improvements to numerical weather forecasting, wild fire management, drought prediction, and aircraft safety. Atmospheric composition papers included science from the A-Train's newest member, the Orbiting Carbon Observatory-2, and recent characteristics of the Antarctic ozone hole. Looking towards the future, there was a special session on new observations, with special attention to missions from Europe such as the Sentinels, ESA's Earth Explorer, and refinements to EUMETSAT operational polar-orbiting satellites. Please turn to page 4 to read a complete summary of the third A-Train Symposium. ■

⁴ ESA's Sentinel missions are designed to meet the operational needs of the Copernicus programme. Each Sentinel mission is based on a constellation of two satellites to fulfill revisit and coverage requirements, providing robust datasets for Copernicus Services. These missions carry a range of technologies, e.g., radar and multi-spectral imaging instruments for land, ocean, and atmospheric monitoring. Learn more at http://www.esa.int/Our_Activities/Observing_the_Earth/Copernicus/Overview4.

The Third A-Train Symposium: Summary and Perspectives on a Decade of Constellation-Based Earth Observations

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Now in full operation for over a decade, the A-Train has transformed our understanding of, and the way we study Earth's interacting systems.

Introduction

The third international A-Train Symposium took place April 17–20, 2017, in Pasadena, CA, and brought 285 scientists together to learn about and exchange scientific findings from data collected by a unique constellation of Earth-observing satellites called the Afternoon Constellation, or “A-Train.” Now in full operation for over a decade, the A-Train¹ has transformed our understanding of, and the way we study Earth's interacting systems. While this article will present a summary of the symposium, we need to begin with some context. We will first address the development of constellation flying concepts and the satellites that make up the constellation. Next, we provide a brief mention of the previous A-Train symposia and—finally—a summary of the third symposium.

Setting the Stage for the Development of the A-Train Concept and its Implementation

When NASA's Earth Observing System (EOS) was first conceived in the late 1980s and early 1990s, the plans called for 30 scientific instruments to be distributed between two large polar-orbiting platforms (EOS-A and EOS-B), supplemented by a Synthetic Aperture Radar mission. (Early plans also called for National Oceanic and Atmospheric Administration (NOAA), European, and Japanese polar platforms.) Large platforms were proposed because the complex scientific questions that EOS was to explore required *continuous* and *simultaneous* observations over Earth's surface and in the atmosphere, which required that the instruments be close together in space and time. Obviously, a suite of instruments on single platforms would achieve that goal.

As inevitably happens, when the theoretical concepts of EOS encountered the rigors of technical and budget realities, compromises and changes took place, and the large platform approach came into question. Risk-averse managers began to wonder: *What if something went wrong with the launch?* Fifteen instruments could be lost in a single launch failure. This led them to ask of the scientists and engineers working for them: *Was there a better way to obtain the same results?* It is perhaps a good example of the old adage: “necessity is the mother of invention.” Previous articles in *The Earth Observer* have described how—and why—the original EOS platforms, which former administrator Dan Goldin once derisively called *Battlestar Galactica*, quickly fell out of favor, evolved through a series of revisions, and eventually became the flight hardware and constellation approach that is in orbit today.² That entire history will not be repeated here, but one detail is particularly pertinent.

In 1991 the Senate Veterans' Affairs, Housing and Urban Development, and Independent Agencies (VA-HUD-IA) Appropriations Subcommittee marked up the Fiscal Year 1992 NASA budget request with language directing NASA to restructure

¹ The term “A-Train” comes from the old jazz tune *Take the A-Train*, written by Billy Strayhorn, and popularized by Duke Ellington. It has become a popular nickname for the Afternoon Constellation, especially since Aqua and Aura are both part of the formation.

² Probably the best overview of the evolution of EOS is “The Enduring Legacy of the Earth Observing System, Part II: Creating a Global Observing System—Challenges and Opportunities” in the May–June 2011 issue of *The Earth Observer* [Volume 23, Issue 3, pp. 4–14—https://eosps.nasa.gov/sites/default/files/0_0_pdfs/May_June_2011_col_508.pdf]. This article references several other articles that give perspectives on various aspects of EOS.

its plans for EOS.³ The language in the appropriations bill called for development of a plan to reconfigure EOS-A and EOS-B into a set of small-to-medium-sized missions and narrow the focus of EOS to global climate change—as distinct from the broader issues of global change, which was the original focus. These two activities were intended to reduce costs and risks across the board. NASA developed a plan and an external engineering review committee (chaired by Edward Frieman, a well-known scientist and, at that time, director of the Scripps Institution of Oceanography) was convened to review it. The Frieman committee essentially affirmed the restructured concept for EOS; they also were the first to suggest what we now know as *constellation flying* concepts⁴ being used with EOS, as a way of achieving its recommendations. Flying some of these smaller missions as a constellation, the committee concluded, would be a more flexible approach (i.e., they could be more easily reconfigured and easier to integrate new technology), a lower-cost and lower-risk way to achieve the same simultaneous and continuous measurements as a large platform would have achieved.

Scientists and engineers began working to fulfill the Frieman committee's vision. The quest to develop a *virtual platform* (instruments from multiple platforms working together in formation, as if they were on a single large platform) began. In 1999 the project scientists for NASA's Terra mission and the joint NASA–U.S. Geological Survey (USGS) Landsat-7 mission (both preparing for launch at the time) signed an agreement to do what they called “loose formation flying.” Landsat 7 and Terra were joined the following year by the Earth Observing-1 (EO-1) satellite from NASA and the Satélite de Aplicaciones Científicas-C (SAC-C) satellite from the Argentine Space Agency [Comisión Nacional de Actividades Espaciales (CONAE)], resulting in a full-fledged orbiting constellation that became known as the *Morning Constellation*, because all the satellites in the formation fly at 705 km (~438 mi) and cross the equator within minutes of one another between 10:00 and 10:30 AM [and also 12 hours later, at 10:00 and 10:30 PM mean local time (MLT)]. More recently, in 2013, Landsat 8 launched into the morning orbit.⁵

The A-Train

In 2002 as NASA's Aqua mission prepared for launch, the concept for the *Afternoon Constellation* was born. It was a similar idea to the Morning Constellation, but this would be a grouping of satellites with a ~1:30 PM (and also ~1:30 AM) local time equator crossing time. The A-Train, as it soon became known, would be a more ambitious engineering and logistical feat because it involved the coordination of more satellites than the Morning Constellation—and also would eventually require carefully planned collaboration with two international partners. **Table 1** lists all satellites that are and have been part of the A-Train, when they joined the constellation, their instrument complements, and the science measurement for each. **Figure 1** illustrates the current A-Train formation and its six satellites. Many more details on the A-Train and the missions that comprise it can be found at <https://atrain.gsfc.nasa.gov>. Please note that missions and instruments described later in the text may be referenced by their names, abbreviations, or acronyms. We ask the reader to refer (back) to this table for relevant details when encountering such references.

³ For more on how the EOS concept evolved over a series of “re”-assessments during the early-to-mid 1990s, see “A Washington Parable: EOS in the Context of Mission to Planet Earth” in the March–April 2009 issue of *The Earth Observer* [Volume 23, Issue 3, pp. 4–12—https://eosps.nasa.gov/sites/default/files/eo_pdfs/May_June_2011_col_508.pdf].

⁴ A good reference for more information on *constellation flying*, and on NASA's Morning and Afternoon Constellations, is “Earth Science Mission Operations...Orchestrating NASA's Fleet of Earth Observing Satellites” in the March–April 2016 issue of *The Earth Observer* [Volume 28, Issue 2, pp. 4–13—https://eosps.nasa.gov/sites/default/files/eo_pdfs/Mar_Apr_2016_508_color.pdf].

⁵ As of today, Landsats 7 and 8 and Terra remain in the Morning Constellation; the SAC-C mission ended in 2013, and EO-1 was decommissioned in 2016. Landsat 5, which had been in orbit since 1984, also became part of the Morning Constellation until the mission ended in 2013.

In 1999, the Project Scientists for NASA's Terra mission and the joint NASA–U.S. Geological Survey (USGS) Landsat -7 mission (both preparing for launch at the time) signed an agreement to do what they called “loose formation flying.”

Table. The A-Train satellites: Instruments, launch dates, and key measurement objectives.

Satellite and Launch Date	Instrument		Measurement
Aqua* 2002	AIRS	Atmospheric Infrared Sounder	Vertical profiles of atmospheric temperature, moisture, and key trace atmospheric constituents
	AMSR-E	Advanced Microwave Scanning Radiometer for the Earth Observing System	Precipitation rate, cloud water, water vapor, sea-surface winds, sea-surface temperatures, ice, snow, and soil moisture
	AMSU-A	Advanced Microwave Sounding Unit-A	Temperature profiles in the upper atmosphere, especially in the stratosphere
	CERES	Clouds and the Earth's Radiant Energy System	Solar-reflected and Earth-emitted radiation
	HSB	Humidity Sounder for Brazil	Humidity profiles throughout the atmosphere
	MODIS	Moderate Resolution Imaging Spectroradiometer	Vegetation, land surface cover, ocean chlorophyll fluorescence, cloud and aerosol properties, fire occurrence, land snow cover, and sea ice cover
PARASOL** 2004	POLDER	POLarization and Directionality of the Earth's Reflectances	Polarized light measurements of clouds and aerosols
Aura* 2004	HIRDLS	High Resolution Dynamics Limb Sounder	Temperature and composition of the upper troposphere, stratosphere, and mesosphere
	MLS	Microwave Limb Sounder	Temperature and composition of the upper troposphere and stratosphere; upper tropospheric cloud ice
	OMI	Ozone Monitoring Instrument	Total column ozone, nitrogen dioxide, sulfur dioxide, formaldehyde, bromine monoxide, aerosol absorption, and cloud centroid pressure
	TES	Tropospheric Emission Spectrometer	Temperature, ozone, carbon monoxide, and water vapor profiles from the surface to lower stratosphere
CALIPSO*** 2006	CALIOP	Cloud–Aerosol Lidar with Orthogonal Polarization	High-resolution vertical profiles of aerosols and clouds
	IIR	Imaging Infrared Radiometer	Nadir-viewing, non-scanning imager
	WFC	Wide Field Camera	Fixed, nadir-viewing imager, single spectral channel covering a portion of the visible (620–670 nm) to match Band 1 of the MODIS instrument on Aqua
CloudSat*** 2006	CPR	Cloud Profiling Radar	Vertical profiles of water amount measured by backscattered radar signals from clouds
GCOM-W1 2012	AMSR-2	Advanced Microwave Scanning Radiometer, second generation	Enhanced understanding of water in Earth's climate system and the global water cycle, and of additional components of Earth's climate system and their interactions
OCO-2 2014	Three high-resolution grating spectrometers		Full-column measurements of carbon dioxide

Undefined Mission Acronyms from Table: *PARASOL*—Polarization and Anisotropy of Reflectances for Atmospheric Science coupled with Observations from a Lidar; *CALIPSO*—Cloud–Aerosol Lidar with Infrared Pathfinder Satellite Operations; *GCOM-W1*—Global Change Observation Mission–Water; *OCO-2*—Orbiting Carbon Observatory-2.

Notes: Glory was to have been part of the A-Train as well. Unfortunately, after its launch in 2011, the satellite failed to reach orbit.

* AMSR-E has not been functional since 2015; HSB has not been functional since 2003; HIRDLS has not been functional since 2008.

** PARASOL exited the A-Train in 2009 and was decommissioned in 2013—exactly ten years after launch.

*** CALIPSO and CloudSat were launched on the same launch vehicle.

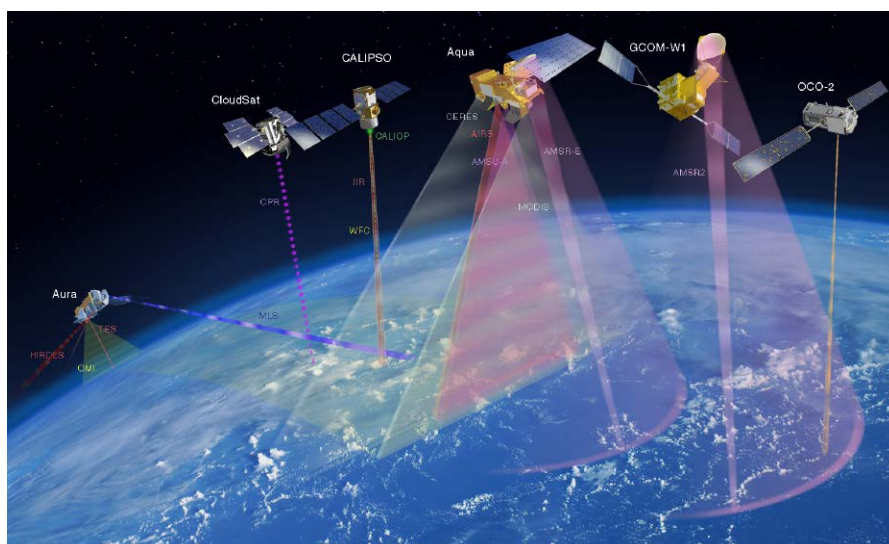


Figure 1. Present configuration of A-Train satellite missions. From right to left, OCO-2, GCOM-W1, Aqua, CALIPSO, CloudSat, and Aura. The "train" orbits from left to right in this representation. The observing "footprint" direction of each instrument is shown for each mission. A unique aspect of the A-Train instruments is that some scan cross-track, or horizontally, across Earth's surface, while others point only to the nadir, or straight down. The train of satellites passes over a given location within about 13 minutes. This timing and complementary viewing capability provide the synergy needed to best characterize Earth-observing parameters, such as clouds and aerosols. **Image credit:** NASA

Previous A-Train Symposia

Two A-Train Symposia were held prior to the one described here. Each was an opportunity for the scientific community that has coalesced around the A-Train missions to come together and discuss results and discoveries coming from this unique constellation. The first symposium was held in Lille, France, in 2007,⁶ when only five satellites were in the constellation. That four-day event provided the first opportunity for investigators to discuss the data synergy afforded by the various A-Train instruments while focusing on the influence of aerosols and clouds on Earth's radiation budget. When the second symposium took place in New Orleans, LA, in 2010, the constellation consisted of the same suite of satellites.⁷ However, the goal of that meeting was to expand the science results from the Lille meeting to include broader synergistic and interdisciplinary efforts, now complemented by modeling and data assimilation.⁸

The Third A-Train Symposium

The third symposium, which is summarized in the remainder of this article, continued the focus of the first two symposia, but also expanded to include results from the two new satellites that had been added to the A-Train since the last symposium in 2010:⁹ GCOM-W1, which focuses on understanding water in Earth's climate system and the global water cycle, and on additional components of Earth's climate system and their interactions; and OCO-2, which focuses on making full column measurements of atmospheric carbon dioxide (CO₂). More specifically, the topics of the symposium talks and posters included cloud processes and radiation, aerosol direct and indirect effects, and atmospheric composition, and their relationship to climate change.

Furthermore, and related to these themes, the symposium included topics on cloud-aerosol interactions, weather prediction, applications, and new missions that will build on and move beyond the capabilities of the current A-Train instruments. There were also oral and poster presentations on algorithm refinements and calibration/validation for the many A-Train data products—not included in this report, but available at

The third symposium continued the focus of the first two symposia, but also expanded to include results from the two new satellites that had been added to the A-Train since the last symposium in 2010: GCOM-W1 and OCO-2.

⁶ A summary of 2007 Symposium appeared in the March-April 2008 issue of *The Earth Observer* [Volume 20, Issue 2, pp. 58-59—https://eospsa.nasa.gov/sites/default/files/eo_pdf/Mar_Apr08.pdf].

⁷ PARASOL entered the A-Train in December 2004. Its orbit was then lowered to 9.5 km under the A-Train in December 2009. PARASOL ended operation, fully exiting the A-Train, in December 2014.

⁸ A summary of 2010 Symposium appeared in January-February 2011 issue of *The Earth Observer* [Volume 23, Issue 1, pp. 12-23—https://eospsa.nasa.gov/sites/default/files/eo_pdf/Jan_Feb_2011_col_508.pdf].

⁹ The Glory mission, which launched in 2011 but unfortunately failed to reach orbit, was also supposed to have joined the A-Train.

Two keynote presentations on the challenges for upcoming Earth system science measurements and the economic value of climate observations were highlights of the symposium.

<https://atrain2017.org/presentations>. Aqua, the first constellation satellite, was launched in 2002, and several of the A-Train missions are now showing their functional age, so an informal report on A-Train flight operations management and the future of the constellation was of particular interest to the attendees.

The very busy three-day symposium included 60 presentations and over 150 poster papers. The event began with representatives from NASA Headquarters (HQ) management on the status of funding and future opportunities in Earth science research. Two keynote presentations on the challenges for upcoming Earth system science measurements and the economic value of climate observations were highlights of the symposium. Summarizing every paper in this brief article is not possible because of space limitations; therefore, only symposium theme highlights and programmatic topics are presented here. Most presentations and poster papers can be found at the A-Train URL listed above.

Management Perspective: Status and Opportunities

Hal Maring [NASA Headquarters (HQ)—*Radiation Sciences Program Manager, A-Train Program Scientist*] greeted the attendees and discussed the overall future of A-Train operations and its member missions. He pointed out that there would be future in-orbit maneuvers by the member missions to maintain their science requirements and adjustments as satellite fuel, needed to maintain formation, is depleted. Maring encouraged the mission scientists to determine how to manage the A-Train formation in light of the fact that the Chinese TanSat mission—a carbon dioxide-measuring satellite launched in December 2016—will periodically fly very close to the A-Train satellites, and could potentially result in a safety concern for the constellation. Finally, he discussed upcoming requirements and opportunities for A-Train mission science analysis, emphasizing the benefits that would derive from multidisciplinary approaches.

Jack Kaye [NASA HQ—*Associate Director for Research of the Earth Science Division*] continued the programmatic discussion with a review of the importance of the A-Train research in NASA's Earth-observation program, and how the activities of U.S. government agencies and international Earth science missions complement the capabilities of the A-Train. Kaye highlighted NASA's collaboration with international environmental working groups such as the United Nations Environment Programme (UNEP), the World Meteorological Organization (WMO), and the Intergovernmental Panel on Climate Change (IPCC).¹⁰ He also acknowledged the participation of the many scientists in NASA's peer review process in maintaining high-quality science. He ended with a broad overview of Earth science funding sources and encouraged optimism, as budget negotiations were underway at that time.

Keynote Presentations: Value and Challenges for Climate Research

Keynote presentations by two senior A-Train scientists are summarized below to provide context for the overall symposium theme discussions that follow.

Graeme Stephens [NASA/Jet Propulsion Laboratory (JPL)—*Director of the Center for Climate Sciences, CloudSat Principal Investigator*] focused on how the A-Train's success points to a bright future for continued Earth observations and their impact on climate research—e.g., see *Moving Beyond the A-Train: EarthCare and Other New Measurements* on page 17. He spoke about how the A-Train enabled new science achievements and made multidisciplinary science possible. Stephens defined the challenge of Earth system science as “explaining the past, understanding the present, and predicting the future.” He described how observations of Earth system science enable prediction of future climate change. On the other hand, data from observations also reveal key biases in community climate models of the Earth system. These biases result from several factors including uncertainties in: sea surface temperatures,

¹⁰ The IPCC was established in 1988 by the WMO and the UNEP to assess scientific, technical and socioeconomic information concerning climate change, its potential effects, and options for adaptation and mitigation. The IPCC has issued a series of reports since 1990; the most recent was the fifth Assessment Report (AR-5), released in 2013.

vertical structure and distribution of cloud types, precipitation amounts, effects of volcanic eruptions, and treatment of the El Niño–Southern Oscillation (ENSO).¹¹ For the future, there is a consensus in the science community that an integrated and balanced measurement strategy is needed using lower-cost measurement systems flying in a constellation, and that science themes should focus on processes more than just individual environmental parameters—a key change in approach, but one that could only have arisen from lessons learned from earlier approaches. Stephens concluded by summarizing how the National Academy’s 2017 Decadal Survey for Earth Science and Applications from Space (ESAS)¹² is formulating consensus recommendations from the Earth science and applications communities for future missions.

Bruce Wielicki [NASA’s Langley Research Center (LaRC)—*Science Team Lead for the Climate Absolute Radiance and Refractivity Observatory (CLARREO) Mission*] gave the second keynote address, which was titled “Economic Value of a New Climate Observing System.” He began by showing how the value of climate science observations might be estimated. Wielicki stated that the use of integrative assessment models (IAMs) is the mainstream methodological approach in climate change research, and that such models rely on climate change disciplines, involve social-economic components as well as natural sciences components, and can then be used for scenario designs. The model can define measurement accuracy requirements for a climate observing system based on the measurement period for detecting climate change, natural variability, and the magnitude of human driven climate change. The accuracy of the system will then drive measurement system cost. Wielicki ended with a demonstration that showed that long-term measurements of shortwave cloud radiative forcing as a climate sensitivity trigger would be more cost effective (by a factor of two) than using a temperature trigger.

Climate Science: Models Benefit from Data

Earth’s *energy balance*, or the idea that the radiant solar energy absorbed by the Earth must equal the energy it radiates back to space, which was once thought to be a fundamental constraint on the climate system.

A revised planetary energy balance framework was suggested, where the top of the atmosphere (TOA) net radiation is parameterized in terms of 500-hPa tropical temperature instead of surface temperature. Model estimates of climate sensitivity (ECS)¹³ based upon the CERES short-term data record compared to estimates that used the “old” framework using surface warming yields a lower ECS than measurements, but is within the IPCC lower range.

The new energy balance formulation is also less impacted by internal climate variability, which may substantially bias previous estimates of ECS derived from historical observations of surface warming. Using the new framework, the observations suggest ECS is likely below the current 3.5-K (6.3-°F) estimate, but is within the IPCC’s AR5 report range. That it falls in the lower end of this range provides some support that models can be further constrained.

Uncertainty in model predictions of ECS result from differences in various parameters, e.g., the extent to which precipitation would change under conditions of increased or continued global warming. In this example, the atmospheric longwave radiative cooling rate predominantly controls global mean precipitation, and is a function of cloud cover. A decrease of high cloud cover leads to increased precipitation because of enhanced longwave radiation loss to space. Analyses using CERES radiative flux measurements

A revised planetary energy balance framework was suggested, where the top of the atmosphere (TOA) net radiation is parameterized in terms of 500-hPa tropical temperature instead of surface temperature.

¹¹ ENSO is an irregularly periodical variation in winds and sea surface temperatures over the tropical eastern Pacific Ocean, which has impacts on weather patterns around the globe.

¹² To learn more about plans for the 2017 Decadal Survey, visit <http://sites.nationalacademies.org/DEPS/ESAS2017/index.htm>.

¹³ The term *climate sensitivity* is often used to specify the equilibrium global mean surface temperature change that results from a doubling of atmospheric CO₂ concentration. However, in this context it is being applied more broadly as a metric to characterize the response of the global climate system to a given forcing.

Since the decline in Arctic sea ice has increased most rapidly during the lifetime of AIRS, its measurements provide an ideal dataset to gain a better understanding of the complex sea ice-ocean-atmosphere interactions occurring in that region.

with MODIS and CALIPSO cloud fraction and water vapor data showed that most climate models underestimate the decrease of tropical high cloud cover with increasing surface temperature. Therefore, models underestimate precipitation increase because of their deficiencies in simulating tropical circulation—particularly the *Hadley circulation*.¹⁴ This result will provide a pathway to improve model predictions of how rainfall patterns will change in response to global warming.

Another study that was described during this session showed that current cloud climatologies, used in climate models, tend to miss optically thin and multilayer clouds or misrepresent the altitudes of these clouds. The errors arise because these climatologies are based on passive measurements, which are often confounded by physical, chemical, and process-oriented complexities of the real atmosphere and thus cannot reveal the vertical distribution of clouds. Such information is critically important for accurately portraying deep convection in models, as well as constructing accurate heating rate profiles. Clouds, coupled circulation, and subsequent feedbacks are still highly parameterized in most current estimates of cloud characteristics, and this leads to uncertainties in determining climate sensitivity.

Several presentations during the session focused on one or more cloud properties and how they contribute to the energy balance at the top of the atmosphere. Most of these studies concentrated on the tropics, using various combinations of A-Train measurements. For example, one presentation described efforts to track upper tropospheric cloud systems feedback using observations from AIRS in synergy with those from AMSR-E, CALIPSO, and CloudSat. In another case, the researchers used CALIPSO opacity observations to provide new constraints on cloud–radiation interaction. Still another presentation made a convincing case that some climate models significantly underestimate thin or broken cloud cover.

There was additional discussion about responses to climate change during which it was noted that, in recent years, the strongest response to climate change is taking place in the Arctic. Along those lines, there were several presentations on the decline in areal extent and thickness of Arctic sea ice. In addition to increasing air temperature, winter *precondition phenomena*—which include water vapor, cloudiness, and circulation changes—account for a significant fraction of the variability in September sea ice extent from the observed long-term downward trend. Since the decline in Arctic sea ice has increased most rapidly during the lifetime of AIRS, its measurements provide an ideal dataset to gain a better understanding of the complex sea ice-ocean-atmosphere interactions occurring in that region. The AIRS data show surface temperatures warming at twice the rate of air temperatures—particularly in fall and winter. Large uncertainties are found in *moisture flux*, or evaporation, and interactions with the surface and low-level clouds. Consequently, these clouds appear to be increasing.

The influence of climate change on regional phenomena, such as weather and global-scale events is difficult to explain, but a possible connection came from an analysis of Aura/MLS, CALIPSO, and aircraft radar observations, which were used to analyze the unusual weather pattern over North America during the winter of 2015–2016. Concurrently, there were anomalously warm sea surface temperatures (SST) in the central Pacific and a shift in convection intensity from the western- to the central-Pacific, with large amounts of cloud-ice near the tropopause leading to increased water vapor in the lower stratosphere. There was even an abrupt change in the usually regular quasibiennial oscillation (QBO)¹⁵ of the winds in the lower stratosphere. The data seem to show a connection between increased SST and changes in the upper troposphere cloud-ice levels, resulting in increased water vapor levels due to enhanced convection. This result showed that increasing lower stratospheric water vapor increases surface temperature and becomes a positive feedback to climate change.

¹⁴ The Hadley circulation is a global scale tropical atmospheric phenomenon in which air rises near the equator, flows poleward at 10–15 km above the surface, descends in the subtropics, and then returns equatorward near the surface.

¹⁵ QBO is a quasiperiodic oscillation of the equatorial zonal wind between easterlies and westerlies in the tropical stratosphere with a mean period of 28 to 29 months.

Cloud Physics and Radiation

Clouds are one of the critical “control knobs” for climate models. The IPCC AR5 report reiterated that clouds remain the largest source of uncertainty in climate projections. Therefore, their influence on climate was a key theme for the symposium. The major sources for cloud data used for the presentations in this session came from CloudSat and CALIPSO; however, several other A-Train instruments provided necessary complementary data.

Despite the uncertainties mentioned above, the IPCC AR5 has acknowledged that A-Train instruments enhance the accuracy of climate model processes because of their ability to vertically resolve cloud information through a combination of passive and active sensors. Over the last 10 years, CALIPSO and CloudSat have characterized the current state and interannual variability of clouds. However, challenges remain with complementary models and climatologies. There is general agreement that current uncertainties in climate sensitivity are largely due to uncertainties in modeling cloud–radiation–climate feedbacks. The nature and extent of these complex feedbacks are uncertain because they are a function of cloud height, cloud cover, and optical depth. However, current measurements from the A-Train, as well as those anticipated from upcoming missions—see *Moving beyond the A-Train* on page 17—have the accuracy and stability needed to monitor cloud characteristic changes over the long term, which will enable observation of their respective responses to climate warming.

Cloud-type distributions vary seasonally and interannually as a function of solar radiation, large-scale atmospheric dynamics, and thermodynamics, which, in turn, regulate the global water and energy cycles. Climate changes can result in changing frequency of a particular cloud type and its distribution, and the combination of these determines cloud feedbacks. A study of 10-year combined CloudSat and CALIPSO cloud-type data products were used to check how well climate models capture the key variations. As an example, the study showed how the *Walker circulation*¹⁶ affected the locations of tropical deep convective clouds, which also shift with the seasons. On interannual scales, ENSO had the effect of shifting the longitude of convective centers.

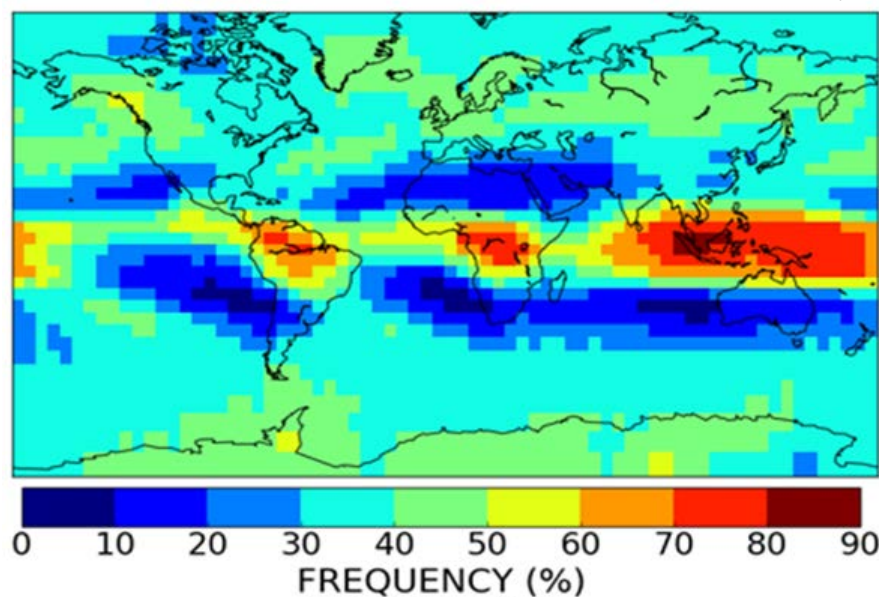
Continuing the cloud type and distribution theme, there were also presentations describing the CALIPSO measurements that were designed to detect aerosols and thin (cirrus) clouds. Results demonstrated that cirrus clouds occur globally at a rate approaching twice what the International Satellite Cloud Climatology Project (ISCCP)¹⁷ had established. At a given time, cirrus clouds overlie 40% of the globe; however, half of these clouds are semi-transparent, making them difficult to resolve with traditional passive sensors from space—see **Figure 2**. Correcting for

¹⁶The Walker circulation is an ocean-based tropical circulation air pattern that influences weather, where easterly trade winds move water and air warmed by the sun towards the west.

¹⁷The ISCCP is part of the World Climate Research Programme with a mission to collect and analyze satellite data to infer the global distribution of clouds, their properties, and their diurnal, seasonal, and interannual variations.

Clouds are one of the critical "control knobs" for climate projections... [and] remain the largest source of uncertainty in climate projections. Therefore, their influence on climate was a key theme for the symposium.

Figure 2. CALIOP 2006-2015 instantaneous annual cirrus occurrence is about 40%. The highest occurrence frequencies are in the tropical convergence zones—near the equator. **Image credit:** James Campbell, U.S. Naval Research Laboratory



Clouds, their convective processes, and how they are parameterized for global climate models continued to be a key theme in this section of the symposium.

unresolved thin cirrus, CALIPSO measurements showed global cloudiness is about 74%, which is in close agreement with ISCCP total global cloudiness, reported as being in the 60-70% range. These measurements provide a more thorough understanding of how cirrus clouds affect the Earth radiation budget overall.

CERES, CloudSat, CALIPSO, and MODIS data were combined to examine the structure of clouds that maintain the radiative balance in tropical convective zones. The net radiative neutrality of tropical convective clouds is a product of the structure and life-cycle of organized tropical convection. Top-of-the-atmosphere *neutrality* (i.e., balance in the Earth's radiation budget) was also shown to be related to the relative abundance of thick versus thin anvil clouds and the life cycle of the anvil cloud produced by tropical convection. This net balance is possible because rainy cores and thick anvils produce a net negative radiative effect, but then they spread out (becoming thinner) and rise to produce a large area of cloud that has a positive net radiative effect.

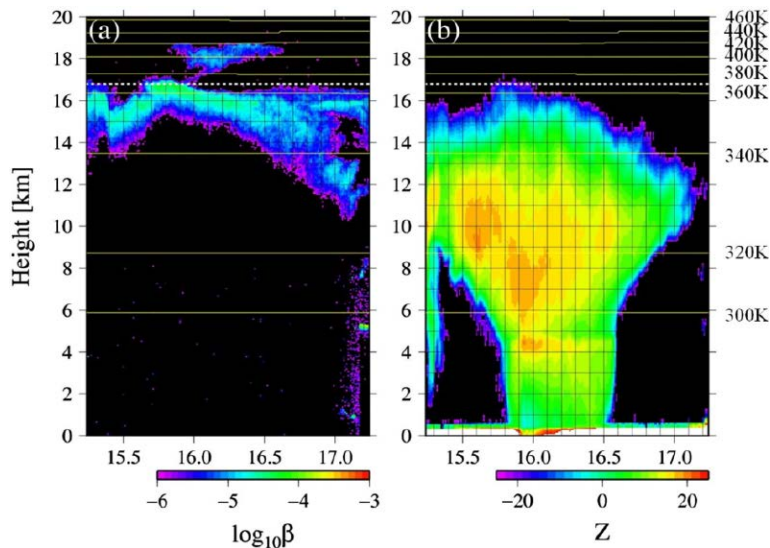


Figure 3. This figure offers an example of how CloudSat and CALIPSO observations complement one another. These data, obtained 120 km (~75 mi) south of Yangon, Myanmar, in May 2007, show latitude-height cross sections of the 532 nm backscattering coefficient β [1/m/str] in log scale measured by CALIPSO's CALIOP [left] and the radar reflectivity factor Z [dBZ] measured by CloudSat's CPR [right]. The white dashed line near the top of each plot denotes the *cold point height* (associated with the *tropopause*) estimated by the European Centre for Medium-Range Weather Forecasts (ECMWF). Notice that CloudSat did not detect the stratospheric cirrus cloud above 17 km (~11 mi) that CALIPSO sees clearly; the cloud likely consists of small ice particles that CloudSat is unable to detect. On the other hand, CALIPSO does not detect any clouds below thick anvil clouds at the height of around 16 km (~9 mi) due to strong attenuation, while CloudSat sees these lower clouds easily. **Credit:** S. Iwasaki, Department of Earth and Ocean Sciences, National Defense Academy, Yokosuka, Kanagawa, Japan

[Below] This photo was obtained from the vantage point of the Space Shuttle *Columbia* on December 10, 1990 over the the Indian Ocean south of the Maldivé Islands. It shows cloudtops overshooting the tropopause into the lower stratosphere. This is the same phenomenon that CloudSat and CALIPSO observed in the example shown in Figure 3. **Photo credit:** NASA



Clouds, their convective processes, and how they are parameterized for global climate models continued to be a key theme in this section of the symposium. Because of space limitations, only one example is given here. CloudSat and CALIPSO each provided a snapshot of a convective cloud, but—as shown in **Figure 3**—combining their data revealed important aspects of convective dynamics, such as mass flux, vertical velocity, entrainment/detrainment, buoyancy, and life cycle. This study also showed how deep convection could result in cloud tops overshooting into the lower stratosphere—see photo, above.

Aerosol Radiative Forcing: Direct Effects

Quantifying the rate of anthropogenic aerosol radiative forcing through direct effects for explaining the past and predicting future climate requires accurate and comprehensive models. However, like clouds, aerosols are another large source of uncertainty in climate models, which show large spreads in clear-sky direct aerosol

radiative forcing. Efforts to resolve this uncertainty have motivated many studies on aerosol composition, optical characteristics, and their temporal and spatial changes, a number of which were described during this session. After being run, models must be tested using observations such as those from the A-Train to constrain aerosol radiative properties. One example of such an effort described during the symposium showed that comparisons of model and measurement-derived direct radiative effects exhibit a seasonal bias, with measurement sampling error likely being one of the causes.

In another study to reconcile measurements and models, the researchers compared aerosol optical depth (AOD) and absorbing aerosol optical depth (AAOD) from different sources. Absorbing aerosols play a role in cloud formation through aerosol-cloud interactions (discussed below in the *Aerosol Indirect Effects* section). Most of these aerosols are black carbon and organic particles produced by human activities, although dust originating from arid land areas is also included. Important as they are, global observations of these aerosols remain sparse. The study compared data from the A-Train (PARASOL and Aura/OMI) with data from atmospheric chemistry models (GOCART¹⁸ and GEOS-5¹⁹), supplemented with information from the Modern-Era Retrospective Analysis for Research and Applications (MERRA).²⁰ Specifically, the comparisons were conducted over Aerosol Robotic Network (AERONET) sites located in regions with heavy aerosol concentrations and in relatively “clean” areas with few aerosol sources. Results were mixed, depending on aerosol types and their local sources (e.g., land, coastal, ocean) pointing to the need for better instrument discrimination and sensitivity and more-accurate aerosol optical property parameterizations to improve model calculations.

The *Asian tropopause aerosol layer*, a dominating and recurring feature associated with the Asian Monsoon, has been studied extensively with ground-based, balloon, aircraft, and satellite data. These measurements showed the aerosols that make up this layer are small, mostly volatile, and composed of a combination of sulfate and organic materials that appear to originate in eastern China and northern India. Another study over the southeast Atlantic region that used data from a variety of A-Train instruments and from the Cloud-Aerosol Transport System (CATS) mounted on the International Space Station (ISS) revealed that the aerosol layer from smoke is much closer to underlying clouds than that shown by CALIPSO. This implies that microphysical processes will have an impact on the direct radiative effect, and that it may have a diurnal component, which—unlike CALIPSO—CATS can observe from its vantage point on the ISS.

Carbon and aerosols cycle between atmosphere and land surface during fire events, and have strong feedbacks to near-field weather, air quality, and longer-term climate systems. One presentation demonstrated that if the height of the fire plume injection is incorrectly estimated, then the transport and deposition of those emissions will also be incorrect. These results were derived using data from multiple A-Train sensors (CALIOP, MODIS) and models [MERRA-2, NOAA Hazard Mapping System, and the Langley Trajectory Model (LaTM)] in multiple ecosystems at a variety of times of day—which is significant because fires peak in late afternoon. **Figure 4** shows an example of smoke transport from active fires that intersect with a smoke-filled

Carbon and aerosols cycle between atmosphere and land surface during fire events, and have strong feedbacks to near-field weather, air quality, and longer-term climate systems.

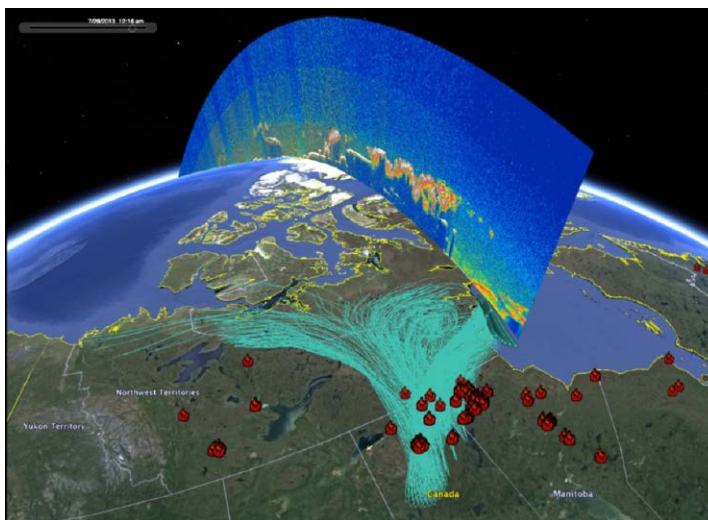


Figure 4. An example of a CALIPSO transect with the Langley Trajectory Model (LaTM) trajectories (shown in the white streams) and active fires (small flame icons). The smoke that has been transported from the fires is detected in the lower level of the CALIOP vertical scans sweeping over the Arctic into Hudson Bay. **Image credit:** Amber Soja, NASA/National Institute of Aerospace

¹⁸ GOCART simulates major tropospheric aerosol components.

¹⁹ GEOS- 5 is a system of integrated models using the Earth System Modeling Framework.

²⁰ MERRA is a long-term global reanalysis to assimilate space-based observations with physical processes in the climate system.

Of particular interest were new results from the OCO-2 satellite, whose primary data product is column carbon dioxide (CO₂) amounts.

CALIPSO transect. In this case, the smoke plume originated in Midwestern Canada, moved eastward across Canada, and deposited onto the Greenland Ice Sheet. Preliminary analysis has shown that eventual deposition of aerosols depends on more than just the intensity of the fire.

Aerosol-Cloud Interactions: Indirect Effects

Aerosol-cloud interactions are responsible for the so-called *indirect effect* of aerosol forcing. In many instances, the presence of aerosols has changed the cloud vertical and horizontal distributions as well as the drop size distributions. Both clouds and aerosols have complex characteristics; therefore, their interactions have inspired intense research.

One study demonstrated that cloud condensation nuclei (CCN) measurements are essential for understanding the role of aerosols in modifying cloud properties. The researchers used satellite measured AOD as a proxy for CCN. AOD derived from the CALIPSO lidar (CALIOP) and CloudSat radar (CPR) provided information on the aerosol vertical distribution for this aerosol–cloud study. The study determined that aerosol extinction in the boundary layer is consistent with continental aerosols being transported offshore. It also found a significant covariability between aerosol extinction in the boundary layer and MODIS cloud droplet number concentration.

Another relevant presentation demonstrated the effect of aerosols on extratropical cyclones, which are a major carrier of precipitation and extreme weather events at midlatitudes. Examining combined observations from CloudSat and CALIPSO, and supplementing with MODIS cloud cover and AOD, the researchers found that cold front clouds, mid-latitude storminess climatology, and MERRA-2 data showed no direct relationship, but concurrent changes in AOD and total cloud cover did suggest some relationship.

Atmospheric Composition: Role in Air Quality and Climate

Several A-Train instruments measure atmospheric constituents important to air quality and climate, where chemistry plays a role in both the troposphere and stratosphere. For the troposphere, pollutants and their precursors were shown to contribute to radiative forcing as well as air quality. Of particular interest were new results from the OCO-2 satellite, whose primary data product is column carbon dioxide (CO₂) amounts. For the stratosphere, there were topics on injection of aerosols through the upper troposphere/lower stratosphere layer and further exploration of the evolution of the Antarctic ozone hole.

Troposphere

It was clear that careful navigation of OCO-2 allowed for synergistic observations with other A-Train satellites and instruments, particularly with CALIPSO and CloudSat, MODIS, AIRS, and OMI. An overview of OCO-2 measurements demonstrated how they helped scientists understand the influence aerosols and cloud distribution and types have on the OCO-2 retrievals of CO₂ and other data products. MODIS cloud screening showed that low clouds are sometimes missed, which can contribute to anomalously low CO₂ estimates.

One study combined OCO-2 CO₂ data with OMI nitrogen dioxide (NO₂) and sulfur dioxide (SO₂) data and MODIS aerosol data into a chemistry transport model (GEOS-Chem)²¹ to simulate East Asian pollution events, resulting in improved

²¹ The GEOS-Chem is a global three-dimensional chemical transport model (CTM) for atmospheric composition driven by meteorological input from the Goddard Earth Observing System (GEOS) of the NASA Global Modeling and Assimilation Office at NASA's Goddard Space Flight Center.

predictions of air quality conditions. **Figure 5** illustrates these measurements on a global scale and shows a clear correlation of pollutants measured from space with those estimated from emission inventories. Fire plumes can also add to poor air quality, but predicting deposition of their polluting constituents depends on accurately estimating their injection height. Furthermore, OCO-2 CO₂ observations were found to correlate with OMI NO₂ data, which can determine anthropogenic CO₂ sources from fossil fuel combustion and natural sources.

OCO-2 solar-induced chlorophyll fluorescence (SIF) observations were correlated with MODIS gross primary productivity (GPP) products to explore the impact of drought dynamics on agricultural productivity. OCO-2 water vapor measurements were compared to measurements from GCOM-W1 and AERONET stations. These comparisons indicate that OCO-2 can make these measurements with high accuracy and spatial resolution, which will be useful in improving numerical weather reanalysis products.

Observations of the vertical distribution of ozone (O₃), carbon monoxide (CO), and methane (CH₄) in the troposphere are crucial for studies of poor air quality effects on human health and vegetation and climate change since these are greenhouse gases. Satellite measurements, e.g., from AIRS, of various chemical species have already shown how data assimilation and chemical reanalysis can observe small changes in space and time, and reconstruct variables not sampled by ground-based networks.

Stratosphere

Turning to the stratosphere, one presentation described how twelve years of Aura/MLS data were used to study climatology and variability of trace gases and cloud water ice during the Asian summer monsoon anticyclone in the upper troposphere and lower stratosphere. The researchers explored the relationships between the observed trace gas behavior and several meteorological factors and climate indices, and found that the abundances of many of the pollutants or their precursors (e.g., CO) peak in June and July—after the monsoon reaches maturity, attaining heights as high as 20 km (~12 mi) into the stratosphere.

CALIPSO has been observing polar stratospheric clouds (PSCs)²² at latitudes up to 82° N and S, since mid-June 2006, and has provided a new database for studying PSC composition and processes. This database can be used to diagnose the evolution of the Antarctic ozone hole, and will evolve into a state-of-the-art PSC climatology, which will be valuable for testing existing and future models of global ozone change.

In a companion study to the PSC database described above, MLS and CALIPSO data were used to study the interannual variations in early winter Antarctic PSC formation that begins Antarctic ozone hole formation, for the period 2006 to 2015. Specifically,

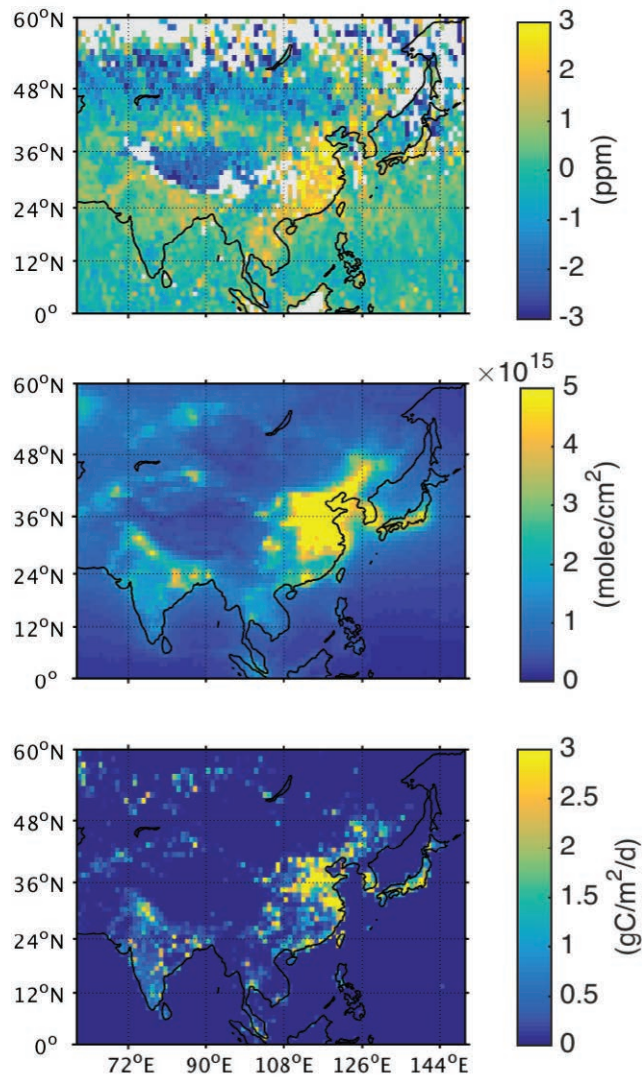


Figure 5. The top plot shows OCO-2 mean total column CO₂ deviations from average column CO₂ in parts per million (ppm). OMI column density NO₂ (molecules/cm²) is shown in the middle plot. The bottom plot shows CO₂ emissions from the Open-Data Inventory for Anthropogenic Carbon dioxide (ODIAC). The data are averaged from 2014 to 2016. **Image credit:** Janne Hakkarainen, Finnish Meteorological Institute

²² Polar Stratospheric Clouds are made up of nitric acid and water vapor crystals and appear in late winter and spring in the Antarctic stratosphere. They provide the pathway for the formation of the Antarctic ozone hole.

The Vapor Pressure Deficit (VPD) data product provided from AIRS measurements of temperature and relative humidity was used with the OCO-2 solar-induced chlorophyll fluorescence (SIF) data product for two U.S. drought events: in 2012 and 2016. They found that their data improved drought early warnings from U.S. Drought Monitor (USDM) if integrated into current operational systems.

the study investigated the MLS nitric acid (HNO_3) evolution and distribution that make up PSCs in the early winter Antarctic vortex, and found that at the very start of the winter, synoptic-scale depletion of HNO_3 can be detected in the inner vortex before the first CALIPSO detection of PSCs.

Weather and Other Applications

A-Train measurements have been tested as operational data for input to numerical weather prediction (NWP) models. For example, tests conducted by the Naval Research Laboratory have shown that assimilation of AIRS radiances into NWP schemes has resulted in a forecast error reduction of 12%. Future satellites flying hyperspectral instruments, with performance similar to or better than CrIS, IASI, and AIRS, will likely improve this result even further. However, aerosol-characteristics data (e.g., from CALIPSO and MODIS) must be properly accounted for, as they can result in significant biases in the temperature profiles used in the predictions.

A Canadian high-resolution global environmental multiscale model for NWP was used to assess the ability to predict high-ice-water content conditions using data from A-Train satellites and *in situ* aircraft measurements at high altitude for aviation safety. In the case studied, CloudSat retrievals of ice water clouds (IWC) were close to the aircraft *in situ* measurements except when the IWC density was high. In addition, the high-resolution model showed the potential to predict the tropical deep convective clouds needed for aircraft safety and operations.

In another application, A-Train data were tested against standard indicators used to predict vegetative drought. Early warning of drought is critical to mitigating drought damage to agricultural products, particularly as droughts are expected to become more frequent and intense with climate change. The Vapor Pressure Deficit (VPD) data product provided from AIRS measurements of temperature and relative humidity was used with the OCO-2 solar-induced chlorophyll fluorescence (SIF) data product for two U.S. drought events: in 2012 and 2016. The researchers found that their data improved drought early warnings from U.S. Drought Monitor (USDM) if integrated into current operational systems. For these two cases, the use of A-Train data improved the lead times by 100 days (2012) and by 40 days (2016) for drought onset. Having begun in April 2017, the performing team is providing USDM with updated VPD and humidity information every week in a near-real-time (NRT) mode.

A poster paper described new capabilities added to NASA's Land Atmosphere Near real-time Capability for EOS (LANCE). LANCE supports application users interested in monitoring a wide variety of natural and man-made phenomena in NRT mode, e.g., for fire management, ash plumes, and flooding. Images from AIRS, MLS, MODIS, and OMI are generally available three-to-five hours after observation. Over the last year, LANCE has been enhanced to include NRT products from GCOM-W1/AMSR2, the Multi-angle Imaging SpectroRadiometer (MISR) on Terra, and the Visible Infrared Imaging Radiometer Suite (VIIRS) on the Suomi National Polar-orbiting Partnership (NPP) satellite. In addition, the selection of LANCE NRT imagery can be viewed interactively through Worldview and the Global Imagery Browse Services (GIBS). This year, LANCE will add data from the Ozone Mapping Profiler Suite (OMPS) on Suomi NPP and the Measurement of Pollution in the Troposphere (MOPITT) on Terra. For more information about these capabilities, visit <https://earthdata.nasa.gov/lance>.

Several other posters further illustrated various applications of A-Train data, including how multiple A-Train instruments and ground-based radars can observe the development of tornadoes, how sea level pressure can be applied to numerical weather predictions and diagnosing the origins of extreme weather, and how knowledge of improved aerosol properties can improve visibility and air-quality forecasts.

Moving Beyond the A-Train: EarthCare and Other New Measurements

Several oral presentations and posters described the European Space Agency's (ESA) implementation of the Earth Cloud, Aerosol and Radiation Explorer (EarthCARE) mission in cooperation with the Japan Aerospace Exploration Agency (JAXA), with launch planned for late 2018. The mission will be in a 2:00 PM local time equator-crossing-time orbit—compared to the A-Train's 1:30 PM crossing-time—and therefore will provide synergistic measurements with the A-Train members. The EarthCARE payload consists of two active (radar and lidar) and two passive (imager and radiometer) instruments. The four instruments will provide three-dimensional (3D) cloud-aerosol-precipitation scenes, with collocated broadband radiation data over the two-year planned mission lifetime.*

There was discussion about state-of-the-art cloud and precipitation radar designs and new imagers planned for the European Organisation for the Exploitation of Meteorological Satellite's EUMETSAT polar-observing systems. There was also a presentation that reported on the requirements for a next generation of the Advanced Microwave Scanning Radiometer (AMSR), which currently flies on Aqua and GCOM-W1, that will have better spatial resolution and a capability to measure snowfall over the ocean. There was a review of GCOM-W1/AMSR2 status and data product accessibility. Another presentation described how a spaceborne multifrequency Doppler scanning radar has been mounted on a NASA aircraft to obtain high-resolution observations of clouds and precipitation. Finally, a compelling presentation described how one might package and operate an AIRS-type instrument on a CubeSat.†

Complementary poster papers included an assessment of the impact of 3D cloud inhomogeneities and multiple scattering on cloud properties measured from the active instruments. Another study combined airborne and A-Train measurements using EarthCARE algorithms with examples of retrieving ice cloud properties from different instruments operating at different wavelengths. There were also posters about simulations that used radiative transfer algorithms and A-Train observations for aerosol retrievals using both the active and passive instruments.

There was also discussion about the application of panspectral radiance measurements, which combine radiance data from multiple instruments over a range of wavelengths (from near ultraviolet to the near infrared) for future missions. These measurements have demonstrated improved ability to measure atmospheric pollutants and greenhouse gases using current instruments. Future panspectral measurements, combined with data assimilation, show the potential to provide synoptic chemical/dynamical situations and accurately quantify long-range transport of ozone, carbon monoxide, and methane profiles at global scales. These measurements will also enable continuation of key EOS measurements begun by the Tropospheric Emission Spectrometer (TES) on Aura and Measurement of Pollution in the Troposphere (MOPITT) instrument on Terra that do not have follow-on missions. The study showed that panspectral observations provide a basis for analysis for the upcoming low-earth orbit (LEO) and geostationary-earth orbit (GEO) air quality and climate constellations.‡

*To learn more about EarthCARE, see "CloudSat-CALIPSO-EarthCARE Science Workshop" in the March-April 2013 issue of *The Earth Observer* [Volume 25, Issue 2, pp. 41-47—https://eosps.nasa.gov/sites/default/files/leo_pdfs/March_April_2013_508_color.pdf].

†A CubeSat is a miniaturized satellite for space research that is made up of multiples of 10×10×10 cm cubic *units*. CubeSats have a mass of no more than 1.33 kg (-2.93 lb) per unit, and often use commercial off-the-shelf (COTS) components for their electronics and structure.

‡ In addition to composition measurements already being made from polar low-Earth orbit, with daily global coverage, composition measurements will be made from a constellation of three geostationary satellites flying over North America, Europe, and Asia with hourly coverage. Two constellations are planned, one for air quality and one for greenhouse gases.

A key lesson learned [from the experience of coordinating the operations of the A-Train] is that close coordination, respect, and communication among all the mission teams are critical for constellation management success.”

—**Bill Guit** [NASA’s Goddard Space Flight Center—Aqua Mission Director]

A-Train Flight Operations: Systems are in Good Health

As noted earlier, the A-Train satellites will eventually run out of fuel and some instruments have failed and others are aging, which raises some concerns about what impact this might have on the Constellation, from the programmatic to the research levels. A poster paper reported on A-Train mission status and flight operations, but the topic drew so much interest that an unscheduled discussion was held during the presentations.

Both the Aqua and Aura satellite buses are in excellent health, even 15 and almost 13 years after their launches in 2002 and 2004, respectively. Neither of the spacecraft has experienced any failures in their subsystems and both are still configured with their primary hardware (i.e., no backups required). Based on past performance, planned propellant usage, and expected degradation rates, the Aqua and Aura spacecraft appear capable of operating within the A-Train until 2022 and 2023, respectively, at which time orbit lowering is necessary to meet end-of-mission, orbit-lifetime requirements. Aqua and Aura can potentially operate into the 2025-2027 timeframe, but would no longer maintain a tight mean local time constraint.

For CALIPSO, the Primary and Redundant laser procedures have been and will continue to be adjusted to avoid operation in the pressure range that would cause laser high-voltage coronal arcing. Unfortunately, CALIPSO is running out of fuel, and will begin to drift out of the A-Train’s present inclination in 2019. The CloudSat mission has indicated they will follow CALIPSO to continue their synergistic measurements (at least until their field of view reaches the edge of the Aqua MODIS swath and then potentially return to the same A-Train location assuming Aqua is still there). However, both satellites are healthy enough to operate for several more years.

It is uncertain what OCO-2 will do about staying in the A-Train, but various options were discussed at the Earth Science Constellation/A-Train Mission Operations Working Group (MOWG) meeting held at GSFC in June 2017. The OCO-2 mission will probably make a final decision before the 2019 series of inclination adjust maneuvers scheduled to begin in March 2019. However, there is enough fuel for OCO-2 to stay with the present A-Train configuration through 2039.

The Japan Aerospace Exploration Agency is working on the long-term plan for GCOM-W1, but the mission will likely stay with the A-Train beyond 2020.

One key lesson learned from the experience of coordinating the operations of the A-Train is that close coordination, respect, and communication among all the mission teams are critical for constellation management success.

Summary

Although the overarching theme of the A-Train 2017 Symposium was climate sensitivity, the diversity of presentations and posters was huge. They included topics on cloud processes, aerosol direct and indirect effects on radiation, and atmospheric composition in the stratosphere and troposphere. The advantage of formation flying was a topic that pervaded nearly all presentations. There were several posters on algorithm improvements and calibration/validation studies for several instruments (not summarized herein). The application and research results from more than a decade of measurements showed that A-Train observations were of sufficient accuracy to improve weather and climate prediction models, although science teams should pursue more data on aerosol–cloud interactions. One-half day was dedicated to upcoming and proposed measurements in the U.S. and abroad that will build upon—and improve—A-Train science and applications. Finally, an impromptu report on flight operations convinced the attendees that continued diligence is needed to ensure the A-Train constellation formation is maintained such that its science goals can be sustained. The good news is that all spacecraft systems are functioning nominally and that operations can continue well beyond 2020. ■

2017 ASTER Science Team Meeting Summary

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Introduction

The forty-eighth joint U.S.-Japan meeting of the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Science Team was held at the Japan Space System's offices in Tokyo, Japan, June 5-7, 2017. The meeting attracted over 40 participants and offered 5 working-group sessions. From the U.S., participants were from NASA's Goddard Space Flight Center (GSFC), NASA/Jet Propulsion Laboratory (JPL), University of Pittsburgh (UP), University of Arizona (UA), University of Washington (UW), and U.S. Geological Survey (USGS). From Japan, participants were from the Japan Space Systems (JSS), Ibaraki University (IU), Nagoya University (NU), University of Tokyo (UT), National Institute of Advanced Industrial Science and Technology (AIST), Sensor Information Laboratory Corp (SILC), National Institute for Environmental Studies (NIES), and Japan Aerospace Exploration Agency (JAXA). The main goals of the meeting were to discuss the:

- status of the ASTER instrument and Terra spacecraft;
- upcoming August 5, 2017, Lunar Deep Space calibration maneuver with the Terra spacecraft;
- release of the Global Digital Elevation Model (GDEM) Version 3; and
- updates on image acquisition scheduling for the following year.

Session Highlights

Opening Plenary Session

Japan and U.S. Science Team leaders **Y. Yamaguchi** [NU] and **M. Abrams** [JPL] opened the meeting and greeted the participants.

J. Hendrickson [GSFC] reviewed the status of the Terra spacecraft, reporting that all systems are operating nominally, with no unusual events since the last team meeting a year ago. He added that fuel consumption is within projected values, and debris avoidance maneuvers have been fewer than last year's.

M. Kikuchi [JSS] reported that the ASTER instrument was operating nominally. He stated that the number of off-nadir pointing maneuvers is within operational limits. He also reported that the visible-near-infrared (VNIR) and thermal infrared (TIR) instruments were operating normally.¹

T. Maersperger [USGS] summarized ASTER-related activities at the Land Processes Distributed Active Archive Center (LPDAAC) over the previous 12 months. He reported that the distribution of ASTER data products has increased by 6-to-10 times since the elimination of charges for ASTER data, starting in April 2016. Maersperger also introduced the Earthdata interface that will replace Reverb² as one of the tools to order ASTER data.

Applications Working Group Discussions

The Applications Working Group provides a platform for team members to present and discuss their science research activities using ASTER data. The majority of work being done is in the disciplines of geology, oceanography, and ecology.

S. Nakamura [JSS] provided an overview of JSS's Space Business Court, both a virtual and brick-and-mortar place where entrepreneurs, researchers, and

¹ The ASTER Short Wave Infrared (SWIR) instrument has not been functional since 2009.

² Reverb was an Earth science data processing tool developed by Earth Science Data and Information Systems (ESDIS).



Attendees at the 2017 ASTER Science Team Meeting held in Tokyo, Japan. **Photo credit:** T. Tachikawa

manufacturers can learn about space-based data, how to add value to remote sensing data, match start-ups with venture capitalists, and provide contacts with engineering companies. The goal is to help the commercial sector use government-sponsored remote sensing data archives and experience. Nakamura also introduced *Fieldnaut*, an Android mobile phone app that combines satellite images, global position system (GPS) technology, photos, and notes to improve the efficiency of field surveys. Finally he presented five international projects sponsored by JSS. Topics included illegal deforestation in Peru, carbon dioxide (CO₂) emissions in Indonesia, mineral recycling in Serbia, lead contamination in Zambia, and wetland management in Uganda.

K. Kurata [NU] presented her research results on combining multiple lithologic indices by using the hue, saturation, and value (HSV) color model—a common cylindrical representation of points that better represents how people relate to color than the common red-green-blue (RGB) model. This novel method of extracting and displaying mineralogical information from ASTER data by transforming mineral indices into HSV color space provides a simple and effective way to display a large amount of information in one interpretable presentation. Kurata showed an example that displayed clay mineral species as hue, clay mineral amount as saturation, additional information on quartz and carbonates as hue, and topography as value—see **Figure**.

D. Pieri [JPL] provided a summary of his work in Hawaii as part of the Hyperspectral Infrared Imager (HyspIRI)³ preparatory campaign, held over the Island of Hawaii in January and February 2017. He explained that the unmanned aerial vehicle (UAV) flights over Kilauea volcano were coordinated with overpasses of the Moderate Resolution Imaging Spectroradiometer/ASTER Airborne Simulator (MASTER) and Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) scanners onboard NASA's ER-2 aircraft, as well as ASTER satellite overpasses. Near-field sulfur dioxide (SO₂) levels of up to 250 parts per million by volume (ppmv) were found, while CO₂ levels ranged up to 500 ppmv. The three-dimensional distributions derived from the UAV data will be compared with spatial gas column abundance from the airborne and spaceborne sensors to improve models of volcanic fog or *vog* that causes pollution as far away as Oahu.

Radiometric Calibration Working Group Discussions

The Radiometric Calibration Working Group is responsible for monitoring the ASTER instruments to

³ More information on HyspIRI can be found at <https://hyspiri.jpl.nasa.gov>. A report on the most recent HyspIRI Symposium appears in the May–June 2017 issue of *The Earth Observer* [Volume 29, Issue 3, pp. 26–30—https://eospsa.gsfc.nasa.gov/sites/default/files/leo_pdfs/May%20June%202017%20color%20508.pdf].

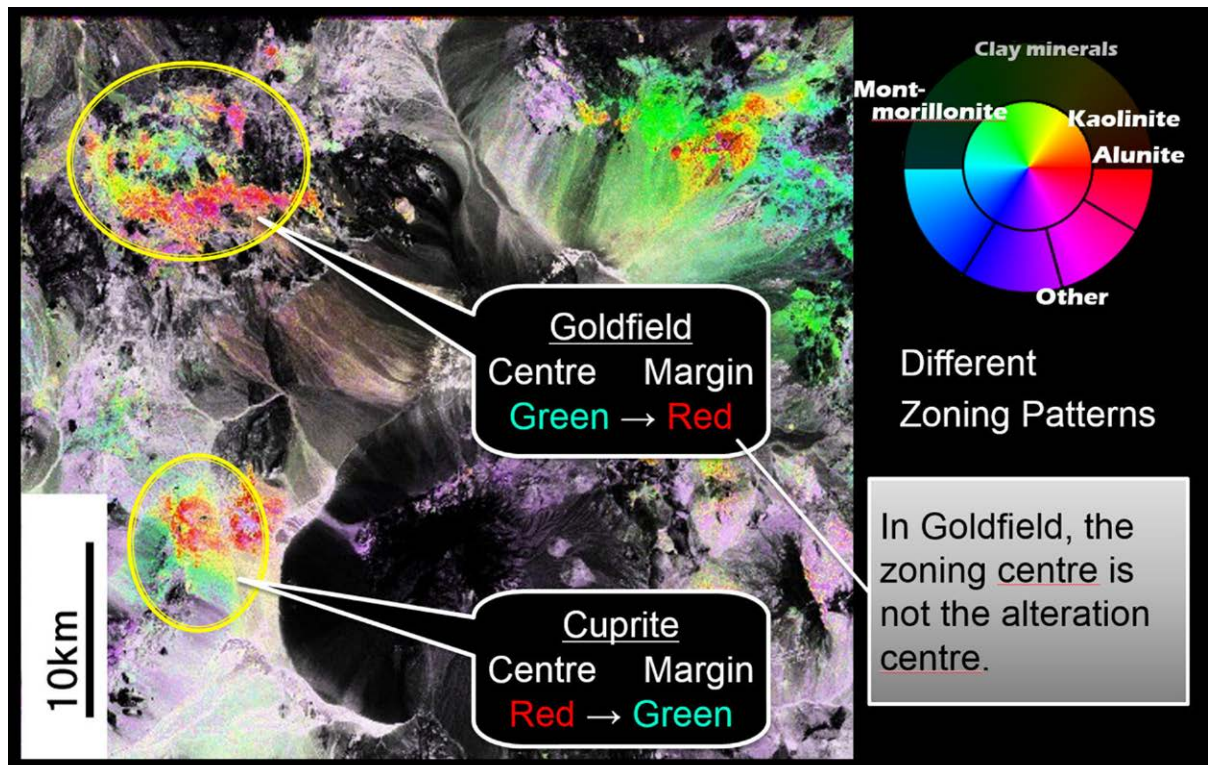


Figure. Example of hue, saturation, and value (HSV) processing of ASTER data to highlight mineral composition as hues, mineral amount as saturation, and topography as brightness. The area is in western Nevada over the Goldfield and Cuprite mining centers; clay and mineral composition (montmorillonite, kaolinite, and alunite) are displayed as different hues. **Image credit:** K. Kurata

understand and characterize their responses to scenes being observed. The group noted that the instrument response is changing smoothly with time. The group also determined updated calibration coefficients to maintain calibration of the data. To monitor the instruments' performance, the team uses data from the onboard calibration lamps for the VNIR channels and onboard blackbody for the TIR, combined with *in situ* field validation campaigns.

F. Sakuma [JSS] reported on the onboard calibration data using two standard lamps. These lamps were calibrated against NIST standards before launch. Their behavior since launch has been monitored with thermistors with well-defined characteristics. As a result, the data are within 1% of the radiometric calibration curves that are used to calibrate the VNIR data. Long-term calibration of the TIR bands, using the onboard blackbody and *in situ* field validation results, continues to be within the threshold of the radiometric calibration curves. In February 2017 the Radiometric Calibration Coefficients (RCC) were updated to reflect small changes in detector responses.

J. Czapla-Myers [UA], **H. Yamamoto** [AIST], **H. Tanooka** [IU], **S. Kato** [AIST], and **M. Abrams** [JPL] presented field campaign results. *In situ* validation experiments are used in conjunction with the onboard calibration lamps and blackbody to assess the instrument performance and to update the calibration coefficients. Field campaigns were conducted in the western U.S. at large playas (the Railroad Valley, Alkali Lake, and Ivanpah playa, all in Nevada) and on Kasumigaura Lake in Japan. In the U.S., data from instrumented, autoreporting validation sites (Lake Tahoe and Salton Sea) supplemented the field campaign results. Despite the fact that the previous nine months had been cloudier than average, sufficient data were acquired to confirm that the instrument VNIR and TIR responses were well understood and characterized.

This session also included an in-depth discussion of the upcoming Lunar Deep Space Calibration maneuver for Terra, which is currently scheduled for August 5, 2017. The Flight Operations Team plans to have Terra perform a 360° pitch maneuver to look at deep space and the moon—repeating an experiment conducted in 2003—to obtain accurate performance and response characteristics for the ASTER detectors. In addition, MODIS and the Multi-angle Imaging Spectroradiometer (MISR) will obtain similar calibration data. The Flight Operations Team, working with each instrument team, has spent the last 12 months scripting and practicing the maneuver.

T. Kouyama [AIST], **S. Kato** [AIST] and **F. Sakuma** [JSS] described several aspects of the experiment, providing a recap of the 2003 maneuver and the results obtained. They explained that the lunar data obtained

in 2003 were used to help calibrate ASTER data and to reveal minor artifacts in the imaging systems. They explained that the 2017 date selected for the maneuver is the best match for the phase angle of the moon relative to Terra such as occurred in 2003. A contingency date in November 2017 has been selected in case the maneuver is waved off (e.g., in the event a debris avoidance maneuver is required).

Level 1-DEM Working Group Discussions

The DEM Working Group evaluated improvements to Global Digital Elevation Model, Version 3, (GDEM3), planned for release in July-August 2017 as an ASTER standard product, replacing the current Version 2.

H. Fujisada [SILC] and **R. Crippen** [JPL] presented similar methods to address the remaining artifacts in GDEM3. They agreed to work together to produce a combined, cleaned-up GDEM3 for release later this summer. This release will have the minimum number of artifacts of any GDEM version, as each successive version is improved from the previous version. GDEM3 will be the final GDEM produced and released by the ASTER project.

H. Fujisada [SILC] discussed corrections and improvements he had made to GDEM3, in version 3.1. Describing his four-step process, he stated that the first step was to replace bad GDEM values with those obtained from Shuttle Radar Topography Mission (SRTM) V3, Alaska DEM, and Canadian Digital Elevation Data (CDED). Fujisada explained that in cases where none of the data sources identified in step one were available, he used GMTED2010 7.5 arc-second data.⁴ Further, he explained that where none of the datasets were available, he used interpolation. Step four was to correct a few errors of land adjacent to shoreline, with SRTM V3 data. Volcanic basalt was incorrectly identified as ocean on Norfolk Island, for example. Fujisada then showed examples where these errors were fixed using this four-step process.

R. Crippen [JPL] presented his work to remove artifacts in GDEM3, mainly the result of cloud edges that were not removed in the compilation procedure. His method was to: mask the errors in GDEM3; mask errors in GDEM2; fill GDEM3 voids with either GDEM2 or SRTM data; and then fill any remaining voids by interpolation. Additionally, Crippen planned to fix tile edge mismatches (unknown source of error), fix errors of places with negative elevations, replace bad Canadian DEM values, fix coastal issues, and increase SRTM fill resolution using newly-reprocessed SRTM

⁴ The 2010 Global Multi-resolution Terrain Elevation Data (GMTED2010) is an elevation dataset from the U.S. Geological Survey and National Geospatial-Intelligence Agency. The data are provided at 30-, 15-, and 7.5-arc-second spatial resolutions.

data. He showed examples to illustrate the effectiveness of his methods.

Temperature-Emissivity Separation Working Group Discussions

The Temperature-Emissivity Separation Working Group is responsible for monitoring and maintaining the algorithms to produce the calibrated temperature and emissivity ASTER products from the Level 1 TIR data. The group monitors the acquisition program that obtains global coverage of Earth's entire land surface. A time-series is obtained by repeating the acquisition scheduling on a regular—i.e., several-year—basis. Repeat coverage allows monitoring of changes to the land surface from natural or anthropogenic causes, such as desertification.

Y. Takahashi's work on estimating oil thickness over water using ASTER thermal data was presented by co-author **H. Tonooka** [IU]. They analyzed data from the Gulf of Mexico's New Horizon spill in 2010 and the Bunga Kelana 3 spill off Singapore in 2010. Their technique is based on an oil-film radiation model described by Matsui *et al.* in 1974 that related the TIR values in different wavelengths, to the thickness of an oil film.⁵ For the New Horizon spill, results from ASTER and MODIS gave consistent and similar results; however, oil thickness near the leak point was smaller than its surroundings because the model was developed for oil films, not for thick oil layers. The second case they analyzed, the Bunga Kelana spill, produced results that were consistent with reported amounts derived from in-water measurements.

H. Tonooka [IU] summarized the progress of the nighttime TIR data acquisition program, the goal for which is to obtain global nighttime TIR coverage on a recurring basis, which would be similar to the coverage for the daytime global mapping activity. The present acquisition program has been operating for the past 23 months. During the near-two-year acquisition of data, about 80% of the targeted areas had been observed at least once under clear sky conditions. Because there are few areas that had not been imaged, the group recommended restarting the nighttime global mapping this month (as if no data had yet been acquired).

Operations and Mission Planning Working Group Discussions

The Operations and Mission Planning Working Group oversees all scheduling of ASTER instruments. Because ASTER acquires data only on demand, a complex scheduling algorithm has been developed to assemble daily schedules for which scenes will be acquired.

Various mapping programs take place simultaneously, such as the global mapping program that operates in the background when no higher-priority acquisitions are scheduled.

M. Fujita [JSS] presented summaries and status updates on all of the ongoing acquisition programs. The Global Mapping-7 program has successfully acquired about 44% of the programmed scenes with 20% or less cloud cover; the group recommended continuing it for at least one more year. The currently running Nighttime TIR Global Mapping was to be suspended, and the next mapping program was to begin, based on recommendations from the Temperature-Emissivity Separation Working Group. The Underserved Area program (an effort to acquire images over persistently cloudy areas) will be continued for at least one more year. The Glacier Monitoring Program will be restarted in the next few months based on recommendation from the Global Land Ice Measurements from Space (GLIMS) project. The Volcano Monitoring Program (which provides frequent day and night coverage of 1500 active volcanoes) will continue for the next few years. The Remote Island Program (which obtains single scenes over isolated mid-ocean targets) will continue. Urgent observations (e.g., field campaigns, volcano monitoring, and natural hazards) were summarized, and the reasons for the 2% failures of the urgent and field campaign requests (3 of 143) were examined individually. The failures occurred because of requests received after the allowed scheduling window had closed.

T. Tachikawa [JSS] presented a summary of the cloud avoidance algorithm performance. By using cloud predictions, data acquisition efficiency increased about 10%.

Closing Plenary Session

The chairpersons of each of the working groups presented summaries of discussions and presentations for each of their sessions. Further discussion of the information presented during the sessions by the entire team was encouraged. The Terra platform and the ASTER instrument are performing normally, with no change since the preceding 2016 team meeting. Continuing discussions about the August 2017 Lunar and Deep Space Calibration maneuver verified that plans were acceptable and the maneuver would be carried out as scheduled. The GDEM Version 3 will be released in summer 2017, pending final correction of the few remaining artifacts. The next meeting will be held June 4-6, 2018, at the same venue in Tokyo. ■

⁵ M. Matsui, Watanabe, K., Yoshida, K., *et al.*, 1974, Hydrocarbon Components of Floating Oil Pollutants of Seawater, *Bull. Japanese Soc. Of Scientific Fisheries*, 40, 111-116.