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The Editor's Corner

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Autumn is now upon us, and the COVID-19 pandemic continues. NASA has made some progress toward returning to in-person work, with NASA's Johnson Space Center and Michoud Assembly Facility currently at Stage 2 on the agency's four-stage framework.¹ However, all other NASA facilities remain at Stage 3, where, with a few exceptions, only mission-essential personnel are allowed onsite. The vast majority of NASA's workforce is still teleworking.

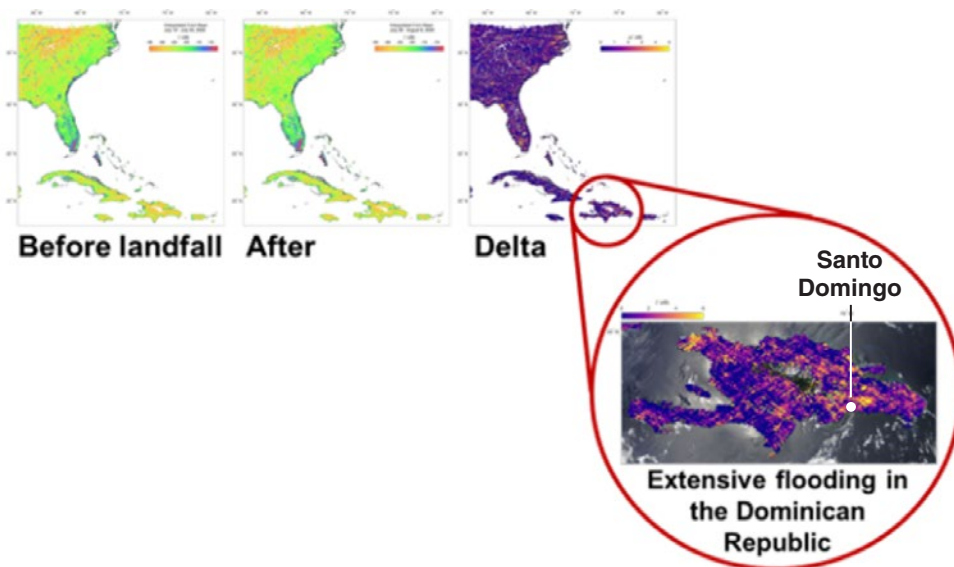
In recent issues, "The Editor's Corner" reported on NASA's ongoing effort to investigate the societal impacts of COVID-19 via remote sensing. Our May–June 2020 issue reported on the funding of the first several Rapid Response and Novel Research in Earth Science (RRNES) science investigations. In July–August 2020, we reported on how NASA has entered into a partnership with the European Space Agency (ESA) and the Japan Aerospace Exploration Agency (JAXA) to create a COVID-19 dashboard (eodashboard.org). In this issue, we report on eight more RRNES projects that have received funding—see the News story on page 27 of this issue.

The public health crisis unleashed by COVID-19 has unfortunately coincided with a series of significant natural disasters.² Even before COVID-19, world attention was focused on devastating fires that impacted Australia in late 2019 and early 2020. Then, a sequence of converging natural disasters hit closer to home this summer: The Western U.S. wildfires and the extremely active—and possibly record-setting—hurricane season in the Atlantic Basin (both of which continue as of this writing). NASA's Earth-observing satellites have been monitoring these phenomena and even their interactions—e.g., see **Figure 1** on page 36. An example of NASA observations allowing researchers to gain a better understanding of fire dynamics and smoke plume evolution is given in the News story on page 31 about the August Complex Fire in California. With regard to the series of 2020 Atlantic hurricanes, the NASA Earth Science Disasters Program featured relevant satellite imagery and datasets at disasters.nasa.gov/tropical-cyclones. This page includes links to pages on Hurricanes Isaias, Laura, Sally, and Delta, all of which made U.S. landfalls. (As of this writing, it appears Hurricane Zeta may be added to this list soon.)

¹ View the framework at go.nasa.gov/37Sepsu.

² Most of the "Recent Events" currently listed on the website for NASA's Earth Science Disasters Program (disasters.nasa.gov) relate to COVID-19, hurricanes, or fires.

continued on page 2



Shown here are Global Positioning System (GPS) surface reflectivity maps from NASA's Cyclone Global Navigation System Satellite (CYGNSS) mission made just before [*left*] and after [*middle*] Hurricane Isaias made landfall in the Dominican Republic on July 30, 2020. The difference (or Delta) between these Before and After maps [*right*] can be used to highlight the regions of most severe flooding. They can be seen in the close-up image of the Dominican Republic as the light gray region on the southeast side of the island near the capital city of Santo Domingo. **Image credit:** Clara Chew [University Corporation for Atmospheric Research]

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NASA's Cyclone Global Navigation System Satellite (CYGNSS) mission was specifically developed to explore the inner workings of tropical cyclones and learn more about the factors that influence their intensity. Launched in 2016, and collecting data since March 2017, CYGNSS uses a low-inclination orbit and a constellation of microsattellites to make frequent measurements of developing tropical storms and throughout their life cycle. With eight satellites in the constellation, there are typically two or three overpasses of a storm every day. This summer and fall, CYGNSS has been making continuous measurements of ocean surface wind speed and flood inundation during the active 2020 Atlantic hurricane season. CYGNSS measurements over land can resolve inland water bodies, which allows the data to be used for practical applications, such as estimating storm-induced flooding—as shown in the images on the front cover of this issue. The combination of pre-landfall measurements of hurricane wind speed and post-landfall flood inundation maps are being used to constrain and test storm surge and flood inundation forecast models.

The Copernicus Sentinel-6 Michael Freilich satellite, a U.S.-European partnership involving several organizations, is scheduled for a November 10 launch aboard a SpaceX Falcon 9 rocket from Vandenberg Air Force Base in California. The spacecraft was flown from Germany and arrived at the SpaceX payload processing facility on September 24, 2020.³ The Sentinel-6 Michael Freilich international collaboration (followed

³ More on the status of Copernicus Sentinel-6 Michael Freilich can be found at go.nasa.gov/34uW6HQ.

by Sentinel-6B, planned for a 2025 launch) will extend the nearly 30-year sea level time series that began in 1992 with the launch of the TOPEX/Poseidon mission and has continued with three more missions over the years: Jason-1, the Ocean Surface Topography Mission (OSTM)/Jason-2 and Jason-3. The satellite was named in honor of NASA's former Earth Science Division (ESD) director who passed away in August of this year and was a pioneering scientist in spaceborne ocean radar scatterometry.

NASA is also busy preparing for two future missions that were selected in 2016 as part of NASA's Earth Venture Instrument (EVI) program.⁴ One will contribute to our knowledge of tropical cyclones and the other to our understanding of how different types of airborne particulate matter (PM)—e.g., from traffic, power plants, or wildfires—affect human health.

The Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS) mission is a state-of-the-science observing platform that will measure vertical profiles of atmospheric temperature and moisture, as well as surface precipitation and tropical cyclone intensity, over

⁴ NASA's Earth Venture program provides a means to develop new science-driven, competitively selected, low cost missions that will provide opportunity for investment in innovative Earth science to enhance our capability to better understand the current state of the Earth system and to enable continual improvement in the prediction of future changes. The three categories of Venture Class missions are: Instrument (EVI), Mission (EVM), and Suborbital (EVS).

the tropical latitudes. Currently, TROPICS is working toward a 2022 launch. The Science Team is testing the ground system, finalizing algorithms, and planning validation methods. TROPICS Applications and the Early Adopter Program continue to interact and discuss the value of TROPICS in applied sciences and short-term weather forecasting. Turn to page 15 to learn more about the status of the TROPICS mission and the applications planned for its data.

The Multi-Angle Imager for Aerosols (MAIA) investigation will add to our knowledge of airborne particles. The instrument, currently scheduled for a mid-2022 launch, contains a pointable pushbroom camera with 14 spectral bands ranging from the ultraviolet to shortwave-infrared. Three of the bands are polarimetric. Assembly, focusing, alignment, and environmental testing of the camera were recently completed in preparation for detailed calibration and characterization. By integrating retrieved aerosol properties with measurements from ground-based PM monitors and outputs of the WRF-Chem atmospheric model, ground data processing will generate 1-km resolution maps of sulfate, nitrate, elemental carbon, organic carbon, and dust concentrations for a globally distributed set of target areas. A team of epidemiologists will use birth, death, and hospitalization records to study linkages to human health in a dozen Primary Target Areas. A set of Secondary Target Areas has also been identified for air quality and climate studies. *The Earth Observer* plans a more detailed coverage of MAIA in an upcoming issue.

Last but not least, I am pleased to report that the feature article in this issue focuses on the NASA ESD's Airborne Science Program (ASP), which is a critical component of the division effort—flying in the “gap” between satellite and ground-based observations. Airborne Earth science goes back to the 1960s, when NASA retrofitted passenger and military aircraft with equipment that enabled collecting *in situ* and remote sensing data for the full range of Earth science disciplines. In addition to acquiring unique datasets, aircraft campaigns play a major role in supporting satellite missions through calibration (i.e., measurements) and validation (i.e., retrieved geophysical products) activities as well as providing a testbed for future satellite remote sensing instruments. The ASP's role in these activities includes Earth Venture Suborbital (EVS) missions that were implemented following the 2007 Earth Science Decadal Survey. Aircraft operations are continuing despite the ongoing pandemic.⁵ Please turn to page 4 of this issue to read a comprehensive report on the ASP. ■

⁵ To find out more about current ASP activities, see the latest issue of the *Explore Airborne Science* newsletter at go.nasa.gov/3jsfuNW.

List of Undefined Acronyms Used in The Editor's Corner and Table of Contents

COVID-19	2019 Novel Coronavirus Disease
EOS	Earth Observing System
JPL	NASA/Jet Propulsion Laboratory
OSU	Oregon State University
SARI	South/Southeast Asia Research Initiative
TOPEX	Ocean Topography Experiment
TROPICS	Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats
WRF-Chem	Weather Research and Forecasting Model coupled with Chemistry

Flying in the “Gap” Between Earth and Space: NASA’s Airborne Science Program

Ernest Hilsenrath, University of Maryland, Baltimore County/Global Science and Technology, Inc., hilsenrath@umbc.edu

NASA’s airborne assets are used to fill in a critical data gap, between satellites above and ground-based measurements below.

Introduction

Established as the nation’s space agency, the link between NASA and space exploration is self-evident. What is not as well known, however, is that NASA also flies in the atmosphere below the “edge” of space, with significant investment in *suborbital* observations made from aircraft that carry instruments to observe phenomena on the ground and take measurements within the atmosphere to gain a “top-to-bottom” picture of the environment to help scientists understand how and why our planet is changing. NASA’s airborne assets are used to fill in a critical data gap between satellites above and ground-based measurements below.



Figure 1. The top photo shows the NASA ER-2 on takeoff. This civilian version of the U-2 spy plane is capable of flying at altitudes greater than 70,000 ft (~21 km) making it an invaluable platform for simulating satellite measurements. The lower image shows the ER-2 in flight during FIREX-AQ, taking measurements high above a smoke plume in California. **Photo credits:** NASA

To give an idea how it works, consider the following scenario:

On a summer morning in July 2019, a NASA aircraft flies through the clear, thin air at 70,000 ft (~21 km) to investigate fires raging over the Northwestern U.S. Known as the ER-2 (shown in **Figure 1**), it is a civilian version of the U-2 reconnaissance aircraft that gained notoriety when it was used for reconnaissance flights over the former Soviet Union, Vietnam, and Cuba during the Cold War between the U.S. and the Soviet Union. Three other aircraft [two de Havilland DHC-6-300 “Twin Otters” from the National Oceanic and Atmospheric Administration (NOAA) and a DC-8 from NASA] fly at various altitudes beneath the ER-2, each equipped with instruments that measure fire and smoke characteristics from wild and agricultural fires. All of these aircraft activities are taking place under the umbrella of a joint NASA–NOAA field campaign called Fire Influence on Regional to Global Environments Experiment - Air Quality (FIREX-AQ).¹ The campaign is a coordinated effort involving U.S. scientists from NASA, NOAA, universities, industry, and representatives from similar institutions from around the world. Each aircraft flight is carefully planned so that the timings of the flights approximately match with overpasses by one or more NASA and international satellites that peer down over this ensemble of aircraft and over similar measurements

being taken on the ground. The overall objective of these coordinated observations is to study the impacts of fire on air quality, weather, and climate and to provide tools for land-use managers to best deploy resources and make predictions not just of fire behavior but for agricultural and other purposes, as well.

This scenario demonstrates how NASA’s Airborne Science Program (ASP), managed from NASA Headquarters, coordinates aircraft operations and science teams with their instruments to organize field campaigns. ASP primarily uses aircraft based at NASA’s Armstrong Flight Research Center (AFRC). However, several other NASA field centers, including Ames Research Center (ARC), Goddard Space Flight Center (GSFC), Glenn Research Center (GRC), Johnson Space Center (JSC), Langley Research Center (LaRC), and Wallops Flight Facility (WFF), provide aircraft and participate in these campaigns.

¹ Further information on FIREX-AQ can be found at <https://espo.nasa.gov/firex-aq/content/FIREX-AQ>.

The importance of airborne campaigns to NASA's Earth Science Division (ESD) activities is well established, as the collected data support all ESD research disciplines, including Air, Climate, Water, Oceans, Ice, and Land. ASP science objectives include calibrating and validating (cal/val) satellite data, conducting campaigns for geophysical process studies, and testing new Earth-observing technologies.

This article provides a brief description of how NASA's aircraft-based Earth-science measurements are implemented. It begins with a brief history of how these measurements became an integral tool for Earth Science research² followed by a description on the various ways ASP supports NASA Earth science research. An example of this is when ASP coordinated the Korea-U.S. Air Quality (KORUS-AQ) campaign that took place in South Korea in 2016. The article also includes a discussion of the unique opportunities ASP provides for students of all ages to get involved in NASA airborne science research.

History

In 1963 NASA and university scientists—envisioning the potential for research at ARC—proposed developing a high-flying jet aircraft for astronomy. This recommendation was met with enthusiasm by the astronomers, and soon thereafter NASA purchased a Convair 990 (CV-990) aircraft—one of the earliest four-engine jet passenger airliners—to conduct airborne astronomical observations. The aircraft was overhauled by removing passenger amenities and installing equipment for astronomical observations, such as an infrared telescope with a gyrostabilized heliostat. The aircraft was appropriately called *Galileo*, and its first mission was to observe the May 1965 solar eclipse over the South Atlantic Ocean.

Galileo flew both astronomy and Earth science missions from 1965 to 1973. In April 1973, when the aircraft was returning from a short flight to test oceanography instruments, *Galileo* collided with a Navy P-3 on approach to Moffett Field, which serves as an airport for both the U.S. Navy and NASA. Tragically, all personnel were lost. NASA replaced the *Galileo* with a similar CV-990, naming it *Galileo II*. Over time, the aircraft was used less for astronomy and more for Earth science. As with the first *Galileo*, the passenger aircraft amenities similarly gave way to instrument racks, data acquisition equipment, and advanced navigational systems, while optical and air-sampling ports replaced some of the windows.

Just like its predecessor, *Galileo II* flew a variety of missions at locations all around the world in support of Earth science. For example, in 1982 the aircraft explored global atmospheric effects from the Mexican El Chichón volcanic eruption. In the mid-1970s, *Galileo II* began satellite-support activities by becoming a platform for testing satellite instruments such as radiometers for the Nimbus series.³ It also flew the first “cal/val” flights, which made near-coincident measurements using instruments similar to satellite instruments so that the data could be directly compared. These flights began in 1972, with the Earth Resources Technology Satellite-1 (ERTS-1), later renamed Landsat 1.

Building upon these early demonstrations of the effectiveness of aircraft for scientific purposes, NASA grew its fleet of Earth-observing platforms. Beginning in 1971 ARC added several more aircraft, including two ER-2s and two Learjet 25s. In addition to testing satellite instruments, the Learjets and ER-2, operating at 50,000 ft (~15 km) and 70,000 ft (~21 km), respectively, enabled the exploration of the upper atmosphere directly with *in situ* instruments—see *An Example of Airborne Research: Exploring the Earth's Ozone Layer* on page 7.

The importance of airborne campaigns to NASA's Earth Science Division (ESD) activities is well established, as the collected data support all ESD research disciplines, including Air, Climate, Water, Oceans, Ice, and Land.

² Much of the content summarized in this section can be found in “Atmosphere of Freedom: 70 Years at the NASA Ames Research Center.”

³ To learn more about the Nimbus series of satellites, see “Nimbus Celebrates 50 Years” in the March–April 2015 issue of *The Earth Observer* [Volume 27, Issue 2, pp. 18–31] [<https://go.nasa.gov/3a9YUd7>].

... in response to NASA's growing fleet of Earth science satellite missions and their requirements for more-sophisticated cal/val and correlative measurements, ASP's aircraft fleet's capabilities evolved—significantly ...

In 1985 Galileo II would suffer a similar fate to its predecessor. In addition to Earth science research, the aircraft was also used for testing landing gear systems. As it was landing after a space shuttle landing gear test flight, the tires caught fire and burned the entire aircraft. Fortunately, there were no fatalities this time. Subsequently, NASA procured a DC-8 aircraft originally owned by Alitalia airlines and then by Braniff Airways. ARC modified the airliner—shown in **Figure 2**—into a flying laboratory to support what was then called NASA's Mission to Planet Earth. The DC-8 had more capability than Galileo or Galileo II—and was fully dedicated to Earth observations. This aircraft is still in use today.



Figure 2. Shown here are two ASP aircraft that have been custom designed to accommodate remote sensing and *in situ* instruments for making Earth observations. The top left photo shows ASP's DC-8. This is NASA's "workhorse" aircraft—both because it can carry heavy payloads and because it is frequently called upon for service. The lower left photo shows the windows on the DC-8 that were modified to accommodate air sampling probes that take *in situ* trace gas and aerosol measurements. The top right image shows the NASA Gulfstream-V (G-V) aircraft. The lower right photo shows the underbelly of the G-V that has been modified to accommodate a waveform scanning lidar to measure sea surface altimetry. This configuration of the G-V was used for Surface Water and Ocean Topography (SWOT) cal/val activities. More details about these two aircraft appear in **Table 1** on page 8. **Photo credits:** NASA

In May 1995 NASA announced the consolidation of most of its aircraft fleet—operational as well as experimental—at Dryden Flight Research Center (DFRC),⁴ located at Edwards Air Force Base in the high deserts of southern California. This decision led to a large outcry of resistance from ARC, other NASA field centers, and the larger research community, claiming that science would be adversely impacted if aircraft used for science observations were moved from their original locations, and that the cost savings were overestimated.⁵

After further analysis and much discussion, the NASA centers came to a compromise, and only the DC-8, ER-2, and two Learjets were moved from ARC to what was then called DFRC, while the remaining aircraft continued their operations out of their respective centers. Subsequently, in response to NASA's growing fleet of Earth science satellite missions and their requirements for more-sophisticated cal/val and correlative measurements, ASP's aircraft fleet's capabilities evolved—significantly, with current capabilities listed in **Table 1**, found on page 8. To demonstrate the utility of such aircraft, a detailed example of the aircraft deployed for a specific airborne campaign, namely KORUS-AQ, is described on pages 12-13.

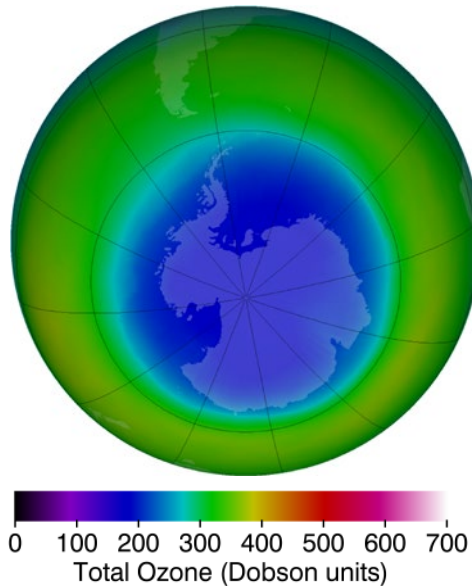
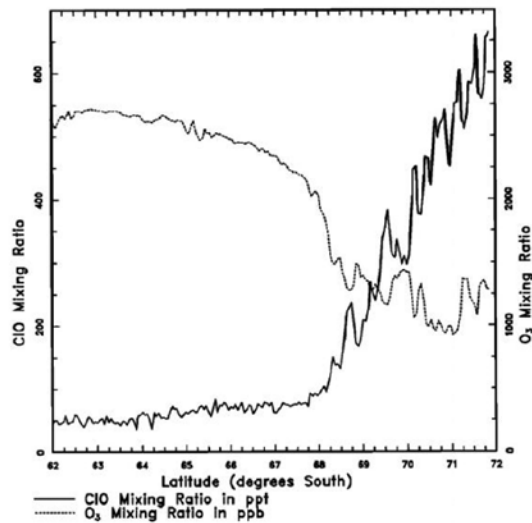
⁴ NASA's DFRC was renamed Armstrong Flight Research Center in 2014 in honor of Astronaut Neil Armstrong.

⁵ Further information on the consolidation of aircraft at DFRC can be found at <https://oig.nasa.gov/docs/HA-96-001.pdf>.

An Example of Aircraft Research: Exploring Earth's Ozone Layer

One research area where aircraft observations have made a significant contribution was the exploration of Earth's ozone layer, in particular by way of the Airborne Antarctic Ozone Experiment (AAOE). In August and September 1987, both the ER-2, flying at 70,000 ft, and the DC-8, flying at 40,000 ft, measured the concentrations and composition of stratospheric gases and aerosols over Antarctica. The data they collected led to the discovery that certain chemicals and aerosols were destroying stratospheric ozone and forming the now-infamous Antarctic ozone hole. The research continued with the two aircraft making similar measurements over the Arctic. The results from these aircraft missions, together with satellite data—examples of which are shown below—laid the foundation in 1987 for the international Montreal Protocol and subsequent amendments limiting the use of chemicals that deplete stratospheric ozone.

ANDERSON ET AL.: SPATIAL AND TEMPORAL EVOLUTION OF ClO-O₃ ANTICORRELATION



Aircraft measurements of atmospheric composition obtained during the AAOE in September 1987 played an important role in helping scientists determine the cause of the annual Antarctic ozone hole. The graph [left] shows the aircraft measurements of ozone (O₃) and chlorine monoxide (ClO) mixing ratios that were obtained as the airplane flew into the hole on September 20, 1987. The image [right] is the map of the Antarctic ozone hole obtained in September 1987 by the Total Ozone Mapping Spectrometer (TOMS) on Nimbus 7. Note the anticorrelation between ozone hole depth and chlorine monoxide concentrations. Ozone hole images like the one shown here have been collected on a regular basis since 1979, via several different NASA instruments on various NASA and non-NASA satellites. For more details, see <https://ozonewatch.gsfc.nasa.gov>. **Image credits:** *Journal of Geophysical Research*, <https://doi.org/10.1029/JD094iD09p11465> [left]; NASA Ozone Watch [right]

Commitment to Earth Science

NASA's ASP is an integral part of NASA's ESD research. The Program complements Earth science satellite missions and all Earth science disciplines, by way of the following ASP commitments to Earth science.

- *Support Satellite Calibration and Validation.* ASP provides aircraft platforms that enable essential calibration of Earth observing satellite instruments and the validation of their data-retrieval algorithms.
- *Support Satellite Sensor Development.* ASP provides opportunities for suborbital flights to test and refine new instrument technologies/algorithms—and thereby reduce risk—before committing satellite instruments to space flight.
- *Support Process Studies.* ASP organizes and conducts comprehensive airborne campaigns that allow for detailed investigations of geophysical processes and evaluation of models and predictions.
- *Develop the Next Generation of Scientists and Engineers.* ASP encourages the development of the future NASA workforce through hands-on involvement of graduate students, young scientists, and engineers in all aspects of Earth science investigations—see *Student Involvement: Future NASA Scientists and Engineers* on page 12.

“NASA is able to implement its world-class Airborne Science Program because of investments in five areas—platforms, sensors, systems, people, and opportunities. [The agency] can deploy a unique mix of physical and human resources into the field when and where needed to address important questions, bridge spatial scales, and advance our overall capabilities in Earth system science.”

— Jack Kaye [NASA Headquarters—Associate Director for Research of the ESD]

Aircraft Capabilities

ASP currently supports seven aircraft at AFRC, GSFC/WFF, JSC, and LaRC—listed in **Table 1**. ASP-supported aircraft receive funding from NASA Headquarters for support costs and personnel, while the investigators fund mission-specific and flight-hour costs. ASP also coordinates with aircraft stationed at other NASA field centers—listed in **Table 2**. Performance, cost, and ability to meet science objectives are the criteria considered when selecting an aircraft.

Table 1. NASA aircraft operating under the auspices of the Airborne Science Program.

Platform Name* (Military Designation)	Center**	Max Flight Duration (Hours)	Useful Payload (lbs)	Max Altitude (ft)	Airspeed (knots)	Range (Nmi)
DC-8	AFRC	12	30,000	41,000	450	5400
ER-2 (2)***	AFRC	12	2900	>70,000	410	>5000
G-III (C-20A)	AFRC	7	2610	45,000	460	3400
G-III	JSC	7	2610	45,000	460	3400
G-III	LaRC	7	2610	45,000	460	3400
G-V	JSC	10	8000	51,000	500	>5000
P-3	WFF	14	14,700	32,000	400	38,000

Table 2. Other NASA aircraft and unpiloted aerial vehicles (UAV).

Platform Name* (Military Designation)	Center**	Max Flight Duration (Hours)	Useful Payload (lbs)	Max Altitude (ft)	Airspeed (knots)	Range (Nmi)
B-200 (UC-12B) “King Air”	LaRC	6.2	4100	31,000	260	1250
B-200	LaRC	6.2	4100	35,000	275	1250
B-200	AFRC	6	1850	30,000	272	1490
(C-130) “Hercules”	WFF	12	36,500	33,000	290	3000
Cessna 206H	WFF	5.7	1175	15,700	150	700
Dragon Eye UAV	ARC	1	1	500+	34	3
HU-25A “Guardian Falcon”	LaRC	5	3000	42,000	430	19,000
Matrice 600 UAV	ARC	1	6	8000	35	3
SIERRA-B UAV	ARC	10	100	12,000	60	600
Twin Otter	GRC	3	3600	25,000	140	450
Viking-400 UAV	ARC	11	100	15,000	60	600
WB-57 (3)***	JSC	6.5	8800	60,000+	410	2500

Notes on Tables 1 and 2.

***Acronyms for Aircraft Designations.** These typically represent the name of the company that manufactured them (e.g., B for Beechcraft; G for Gulfstream), the purpose of the aircraft (e.g., C for Cargo; P for Patrol), or some combination thereof. For example, ER stands for Earth Research; the WB-57 is a modified Bomber, with the W standing for Weather. A more detailed list of these aircraft with links to description of each aircraft type can be found at <https://go.nasa.gov/3j2P1Cg>. For a visual summary of the NASA aircraft, see <https://airbornescience.nasa.gov/tracker/#status>. (This site also lists several NOAA aircraft.)

****Acronyms for NASA Centers.** AFRC: Armstrong Flight Research Center; ARC: Ames Research Center; GRC: Glenn Research Center; JSC: Johnson Space Center; LaRC: Langley Research Center; WFF: Wallops Flight Facility.

***(*Numbers in bold, italicized parentheses*). Denotes there is more than one identical version of this type of aircraft.

Each NASA aircraft has unique performance characteristics and can be custom fitted for each campaign. For example, ports for remote sensing instruments can replace windows. Several aircraft also have provisions for mounting air-sampling instruments around the exterior of the fuselage, placing them along much of the length of the aircraft—see bottom photos of Figure 2 on page 6.

Since 1987 the ASP has managed at least 45 campaigns around the world, including at both Poles.⁶ As an example, **Figure 3** shows the regions and flight paths covered in 2016 (the year for the campaign example described later).

2016 Airborne Campaigns

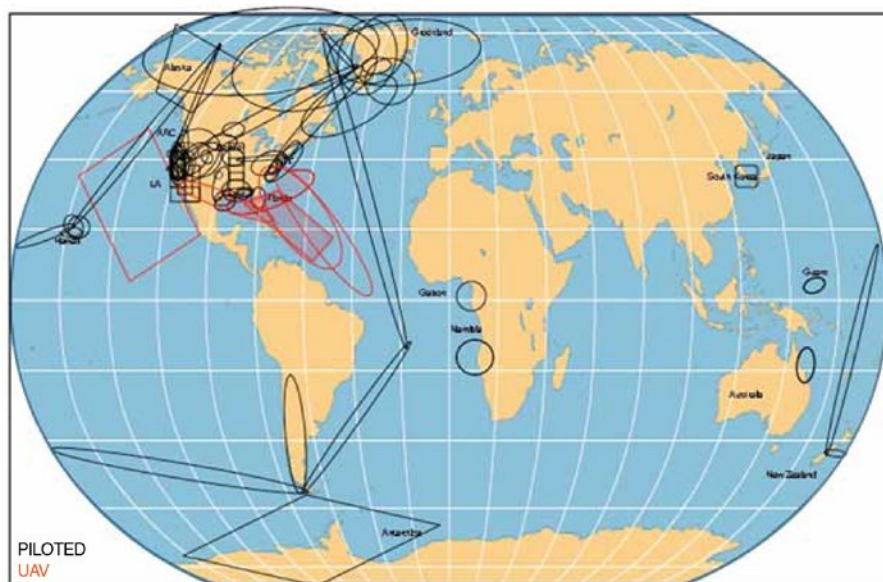


Figure 3. This is an example of the coverage of the 14 missions ASP deployed in 2016, the year for the example campaign described below. The black lines show the flight paths for that year. ASP also operated an unpiloted aerial vehicle (UAV; flight paths shown in red), which was subsequently deleted from the ASP fleet. **Image credit:** NASA

Since 1987, the ASP has managed at least 45 campaigns around the world—including at both Poles.

NASA maintains close relationships with other government agencies when there are common interests. For example, the agency has a long and fruitful history of collaboration with NOAA, e.g., with Earth observing satellite missions. When conducting aircraft campaigns, each agency often shares resources, making use of complementary capabilities. FIRE-AQ and AAOE are two examples discussed in this article. Other examples can be found at the website referenced in footnote 6.

Engineering and Operational Support

Once NASA approves a mission and instrument principal investigators are selected, ASP provides assistance and advice during all phases of the mission. Engineering support includes assisting with instrument integration into the aircraft including compartment selection, mounting, and window selection (if applicable). ASP also makes available access to its data network and provision of test flights.

In addition to engineering support, ASP can guide the aircraft selection process based on the mission's science requirements and aircraft capabilities. ASP personnel are also available to help develop a mission operations plan that includes aircraft type, flight plans, schedules, and cost. Application through the Science Operations Flight Request System⁷ is ASP's formal process for a research scientist to request campaign support.

⁶ Links to details about each activity are provided by the campaign logos for all ASP-supported activities shown at <https://go.nasa.gov/375xw29>.

⁷ To learn more about this system, visit <https://go.nasa.gov/2SZHLwt>.

MTS was first deployed in 2011 for the Airborne Tropical Tropopause Experiment (ATTREX) campaign. Since that time it has been used in nearly every major NASA Earth airborne science investigation.

Facility Instruments

Several NASA *facility instruments*—remote sensing systems that can support a variety of NASA science objectives—are available for use by mission and instrument scientists.⁸ They include visible, infrared, and radar imagers, topography lidars, air temperature and humidity sounders, and other supporting measurement modalities. These facility instruments have a proven track record of performance and can make measurements that apply to several science disciplines. In this way, mission scientists do not need to develop their own instruments for their experiments. Some of these instruments are versatile enough that they can be deployed on several of the aircraft listed in Table 1 on page 8. This affords additional options for mission scientists to select an aircraft that meets their science requirements and still take advantage of the capabilities of a facility instrument.

An example of a widely used facility instrument is the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS), a spatially scanning spectrometer that measures the upwelling spectral irradiance covering the wavelength range from 380 nm to 2500 nm. Data from this instrument can be applied to studies in the fields of oceanography, hydrology, geology, volcanology, soil and land management, and atmospheric composition.

The Mission Tools Suite

ASP also supports the Mission Tools Suite (MTS),⁹ which provides a means for visualizing the position of an aircraft during the course of a mission. Using MTS, an aircraft track can be positioned over satellite images or model output, thus providing an overall picture of the region where aircraft measurements are being made. The MTS can also be used preflight for mission planning or postflight for science data analysis. During flight, MTS provides the communication between aircraft and the ground, and integrates various information sources to a common operating venue. For example, communications between the inflight mission team and weather forecasters on the ground can help direct aircraft to the intended target area or help the team avoid certain areas because of poor viewing, all the while maintaining aircraft safety.

In addition to mapping and visualizing aircraft locations, MTS can plot various aircraft and instrument data as a function of time. A built-in chat feature helps facilitate real-time communication between mission team members during science campaigns.

MTS was first deployed in 2011 for the Airborne Tropical Tropopause Experiment (ATTREX) campaign.¹⁰ Since that time it has been used in nearly every major NASA Earth airborne science investigation. It is also regularly used by the NOAA Atlantic Oceanographic and Meteorological Laboratory (AOML) for its annual tropical-storm tasking and hurricane-research program.

Figure 4 on page 11 shows an example of the MTS being used during the Aerosol Cloud meteorology Interactions over the western Atlantic Experiment (ACTIVATE), the objective of which is to characterize aerosol-cloud-meteorology interactions using *in situ* and remote sensing airborne measurements. The MTS screen shows the position of an aircraft during the course of the mission overlaid on a Geostationary Operational Environmental Satellite-16 (GOES-16) Channel 13 map. This channel is used for detecting clouds—day and night—and is particularly useful

⁸ Further information about facility instruments can be found at <https://go.nasa.gov/3dCwU5m>.

⁹ For more information on the MTS, visit <https://go.nasa.gov/2FCXfUk>.

¹⁰ ATTREX was an Earth Venture Sub-Orbital (EVS) mission, which is a class of Earth science missions that focus on conducting research using aircraft, balloons, sounding rockets, and other suborbital assets. To learn more, see <https://essp.nasa.gov/projects>.