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Editor's Corner

Steve Platnick
EOS Senior Project Scientist

In this issue we highlight the path of data from satellite to product to distribution. The Earth Observing System Data and Operations System (EDOS) is responsible for acquiring, processing, and delivering instrument data to the ground for many of NASA's Earth-observing missions, including the EOS Terra, Aqua, and Aura platforms. The overall objective of the Earth Observing System Data and Information System (EOSDIS) is to process, archive, and distribute Earth science data—from both NASA and other agencies—to the user community. Toward that end, EOSDIS consists of processing facilities at science data centers distributed across the U.S. Not only does EOSDIS provide services for NASA satellites, it also provides archive services for several international missions, as well as data from airborne missions (e.g., IceBridge), field campaigns, and *in situ* measurement programs. To learn more about EDOS and EOSDIS please see the feature article on page 4 of this issue.

On February 19, 2017 at 9:39 AM EST, a SpaceX Falcon 9 Dragon spacecraft (Commercial Resupply-10) lifted off from Launchpad 39-A at Cape Canaveral in Florida carrying two NASA missions to the International Space Station (ISS): the Stratospheric Aerosol and Gas Experiment III (SAGE III) and the Lightning Imaging Sensor (LIS). This was the first launch from Launchpad-39-A since the last Space Shuttle launch in 2011.

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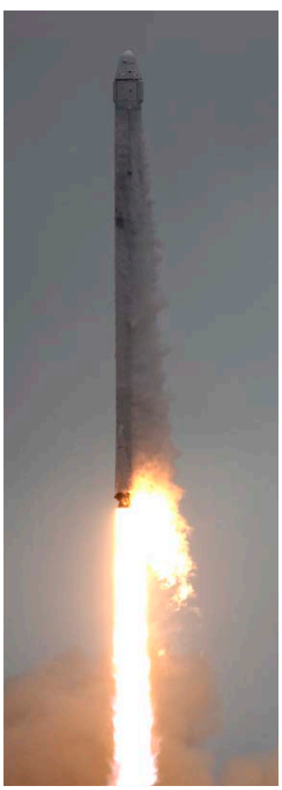

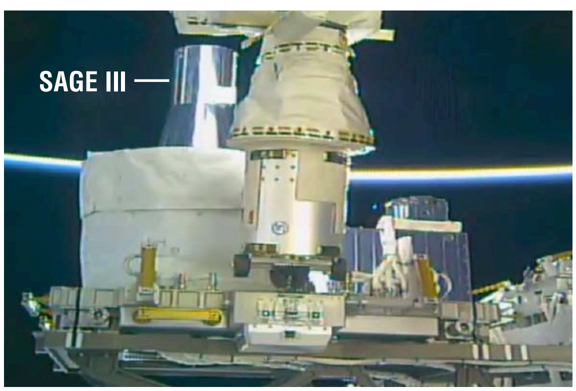

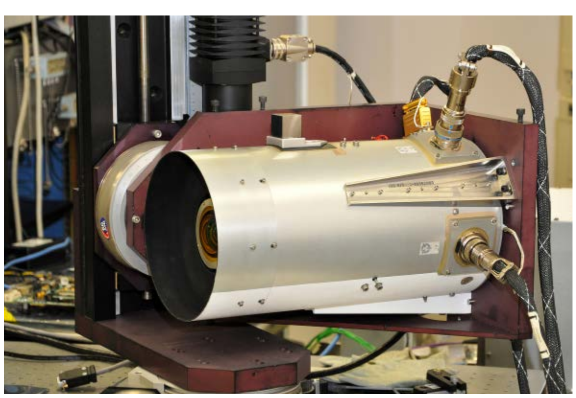

NASA has successfully installed two more Earth-observing instruments on the International Space Station (ISS). The photo on the left, taken on February 19, 2017, shows a SpaceX Falcon 9 Dragon spacecraft (Commercial Resupply-10) as it lifted off from Cape Canaveral in Florida carrying the Stratospheric Aerosol and Gas Experiment III (SAGE III) and the Lightning Imaging Sensor (LIS). The top right photo shows SAGE-III installed on ExPRESS Logistics Carrier 4 (ELC-4) on the ISS, perched upon its Nadir Viewing Platform that allows it to look straight down. LIS was successfully installed on ELC-1. The lower right photo shows the LIS instrument when it was being calibrated in the laboratory at the University of Alabama in Huntsville back in 2014. **Photo credits:** NASA

In This Issue

Reminder: To view newsletter images in color, visit *eospso.nasa.gov/earth-observer-archive.*

In a highly choreographed, four-day sequence of events ending on March 7, the ISS's robotic Canadarm2 removed the SAGE III on ISS Instrument Payload and its Nadir Viewing Platform from the trunk of the SpaceX Dragon capsule and installed them on the ExPRESS Logistics Carrier 4 (ELC-4) platform. The first data were obtained on March 17, with team members confirming several successful solar occultations. The instrument is now collecting preliminary ozone and aerosol data. The SAGE III mission operations team, based at the Flight Mission Support Center at LaRC, is continuing commissioning, which is expected to be complete by mid-May. Data are expected to be freely available to the public beginning in late August.

SAGE III on ISS will monitor the condition of stratospheric ozone. Its predecessors, SAGE I, SAGE II, and the first SAGE III,[1] which were all mounted to "free-flying" satellites, helped scientists understand the causes and effects of the thinning ozone layer. SAGE III on ISS, designed to operate for no less than three years, will allow scientists to continue monitoring its expected recovery.[2]

[1] There were three identical copies of SAGE III built. The first flew on the Russian Meteor-3M satellite from 2001 to 2006; the second is now installed on ISS; the third is in storage at LaRC.

[2] To learn more about SAGE III on ISS, read "SAGE III on ISS: Continuing the Data Record" in the November–December 2015 issue of *The Earth Observer* [**Volume 27**, **Issue 6**, pp. 4-11].

LIS is a hosted payload on the Space Test System-Houston 5 (STS-H5), which has been successfully installed on ELC-1 on the ISS. LIS was powered up on February 27, and successfully executed its functional checkout. Control of LIS was transferred to the LIS Payload Operations Control Center (LIS POCC) at MSFC on February 28. It has been continuously collecting science data since then. Real-time processing at two-minute intervals has also successfully been underway since its power up. The LIS team is still assessing the data and products before a public release, which is expected to occur in the near future.

First launched as an instrument on the Tropical Rainfall Measuring Mission (TRMM) in 1997, LIS records the time, energy output, and location of lightning events, day and night. From its perch on the ISS, the new LIS will improve coverage of lightning events over the ocean and also during Northern Hemisphere summer months. Because lightning is both a factor and a proxy for a number of atmospheric processes, NASA as well as other agencies will use the new LIS lightning data for weather forecasting, climate modeling, air quality, and other studies.[3]

[3] To learn more about LIS on ISS, read "LIS on ISS: Expanded Global Coverage and Enhanced Applications" in the May–June 2016 issue of *The Earth Observer* [**Volume 28**, **Issue 3**, pp. 4-14].

Meanwhile, the Total Solar Irradiance Sensor (TSIS-1) is scheduled to launch in November 2017, joining the growing list of NASA missions installed on the ISS.[4] The TSIS Project conducted a successful two-day Delta Pre-Environmental Review February 8-9, 2017. TSIS-1 will measure total solar irradiance (TSI), the sun's total energy input into Earth, and solar spectral irradiance (SSI), the distribution of the sun's spectral energy which helps us understand how the atmosphere responds to changes in the sun's output. TSIS-1 comprises two instruments, both provided by the Laboratory for Atmosphere and Space Physics (LASP) at the University of Colorado: the Total Irradiance Monitor (TIM) and the Spectral Irradiance Monitor (SIM). These measurements continue the measurement record made by the TIM and SIM instruments on the Solar Radiation and Climate Experiment (SORCE) since 2003, and the TIM instrument on the TSI Calibration Transfer Experiment (TCTE)[5] that has been in orbit since 2013.

Our last issue reported on the launch of CYGNSS. We can now report that all eight spacecraft have successfully completed their engineering functional checkouts and are able to perform regular science operations. Six are in science operations mode and two are in "high drag" mode, in which the spacecraft is pitched up to maximize atmospheric drag and lower the higher satellites down to the altitude of the lower ones. This is a routine constellation configuration management procedure that is used to adjust the relative spacing between spacecraft. One or two spacecraft will be placed into high-drag mode for several weeks each between now and the start of the Atlantic hurricane season, after which all eight will be kept in science mode until autumn to maximize storm coverage. Calibration of the science data is currently underway, after which validation of the science data products will begin. The calibration/validation process is planned to be completed prior to June 1, and public release of the data products will begin at that time.

As new missions move forward, existing missions reach milestones. The joint NASA–German (DLR/GFZ) Gravity Recovery and Climate Experiment (GRACE) celebrated the fifteenth anniversary of its launch on March 17, 2017. GRACE has lasted three times as long as originally planned—a remarkable achievement and a testament to the hard work of the team. GRACE monthly mean gravity fields have provided unprecedented insight into groundwater and surface-water change, polar ice sheet and glacier melt, sea level change, and ocean and land-mass changes. As a result, GRACE data are being used for drought monitoring and disaster prevention and forecasting.[6]

In 2010, NASA recognized the need for continuity of the critical observations provided by GRACE. Since 2012, NASA and GFZ have been working on GRACE Follow-On (GRACE-FO), with Germany again procuring a launch vehicle and the twin satellites built by Airbus in Germany. The GRACE Mission Operations Team is doing everything possible to extend the life of the mission to achieve overlap with GRACE-FO, currently scheduled for launch between December 2017 and February 2018. The new mission uses similar hardware as GRACE but will also demonstrate a new laser ranging instrument technology to measure the separation distance between the satellites. The laser instrument has the potential to produce even more accurate gravity measurements.

The Earth Observing-1 (EO-1) mission was passivated on March 30, reaching the end of its successful and long (17 years) run. Commissioned as part of NASA's New Millennium Program, the satellite was part of a series of low cost missions that were developed to test new in-flight technologies and concepts. The two instruments on EO-1 were the Advanced Land Imager (ALI) and the Hyperion hyperspectral imager, both of which were pathfinders for current or planned instruments. Several successful technology developments and demonstrations were achieved by the mission, as well as new science made possible with a full spectrum hyperspectral imager. To learn more about the accomplishments of EO-1 please refer to the news story on page 39 of this issue.[7] ■

See page 18 for list of undefined acronyms used in the editorial and table of contents.

[4] In addition to SAGE III and LIS, the Cloud Aerosol Transport System (CATS) is also currently installed and active. The Rapid Scatterometer (RapidScat) ended a two-year mission on ISS in September 2016. Additional launches are scheduled in the next few years. For details see https://www.nasa.gov/feature/goddard/2017/earth-science-on-the-space-station-continues-to-grow.

[5] TCTE flies on the U.S. Air Force's Space Test Program spacecraft known as STPSat-3.

[6] These achievements were described in "Assessing the State of GRACE@10" in the March–April 2012 issue of *The Earth Observer* [**Volume 24**, **Issue 2**, pp. 4-13]. A more recent release can be found at *https://grace.jpl.nasa.gov/news/89/grace-mission-15-years-of-watching-water-on-earth*.

[7] EO-1's remarkable story is told in even greater deatail in, "EO-1: 15 Years After the Start of Its 'One-Year' Mission" in the January–February 2016 issue of *The Earth Observer* [**Volume 28**, **Issue 1**, pp. 4-14].

Earth Science Data Operations: Acquiring, Distributing, and Delivering NASA Data for the Benefit of Society

Ernest Hilsenrath, University of Maryland Baltimore County, Global Science and Technology, Inc., hilsenrath@umbc.edu
Jeanne Behnke, NASA's Goddard Space Flight Center, jeanne.behnke@nasa.gov

NASA's current fleet of 21 Earth-observing missions, which include free-flying satellites as well as several onboard the International Space Station (ISS), produce roughly 11,000 data products that cover the full range of Earth-science disciplines.

Introduction

Picture this: A NASA Earth-observing satellite flying 700 km (~435 mi) above Earth and moving at about 28,000 km (~17,400 mi) per hour passes over a raging wildfire in Southern California. From its polar-orbit vantage point, an onboard optical sensor converts the fire's radiation to a stream of electrons, which are subsequently sent to the ground. These data are then processed by an algorithm that registers the data as a fire. These data are archived and distributed to many users, such as the U.S. Forest Service (USFS), who utilize the data to track and analyze fires on a routine basis, enabling them to strategically plan for future fires anywhere in the U.S.

The scenario described above is just one example of how data obtained from Earth-observing satellites are being transformed into applicable information that benefits society. **Figure 1** shows NASA's current fleet of 21 Earth-observing missions, which include free-flying satellites as well as several onboard the International Space Station (ISS). These missions produce roughly 11,000 data products that cover the full range

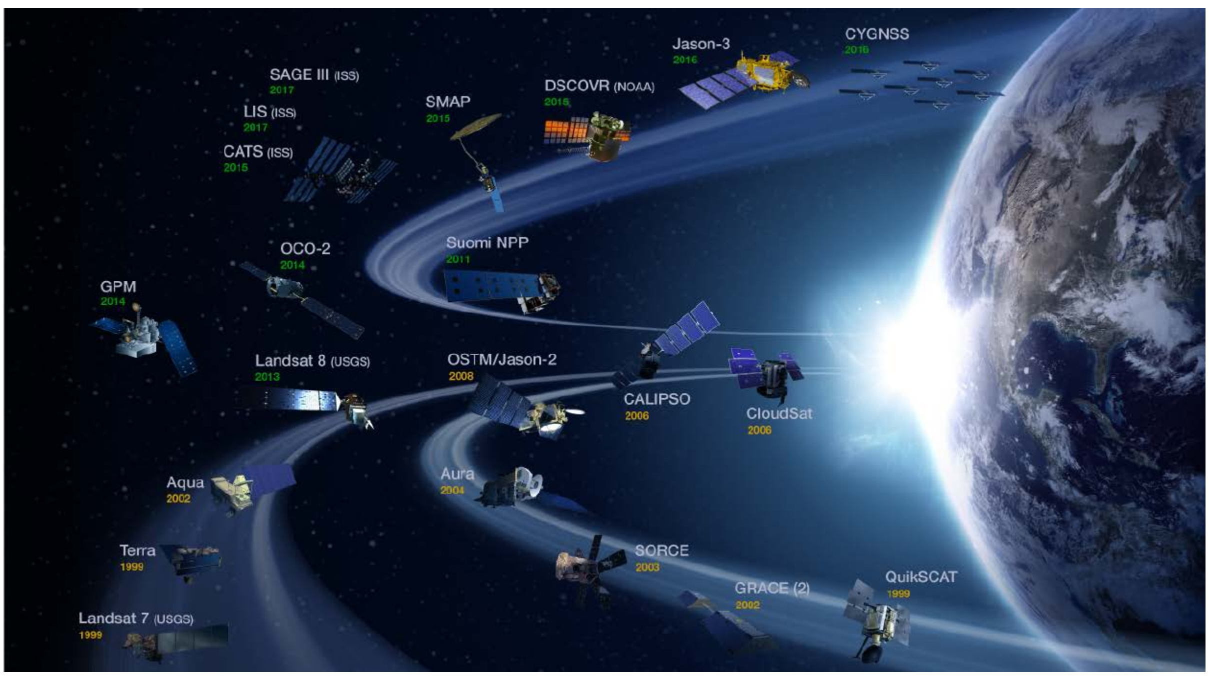

Figure 1. NASA's current Earth-observing fleet includes 21 missions. Of these, three are payloads onboard the International Space Station (ISS). This diagram does not represent the orbital tracks of each mission or the groupings of satellites. **Image credit:** NASA

of Earth-science disciplines, e.g., physical oceanography, global hydrology, atmospheric composition and dynamics, biogeochemistry and ecology, land processes, crustal dynamics, precipitation and snow cover, and solar energy and Earth's radiation budget. These data are produced from instruments that measure the amount of radiation either reflected or emitted from Earth across the spectrum from the ultraviolet to the microwave region.[1] In a previous article, we described how the Earth Science

[1] The notable exception would the Gravity Recovery and Climate Experiment (GRACE) where the satellites themselves are the "instruments" and the measurements made are not of electromagnetic energy, but rather changes in distance between the two satellites as their respective orbital positions are influenced by changes of mass distribution of the planet beneath them.

Mission Operations ESMO Project[2] at NASA's Goddard Space Flight Center (GSFC), is responsible for *flight operations:* the safe operation and management (command and control) of NASA's satellites while maximizing data collection to ensure the continuity and quality of NASA's Earth-science data.

The second ESMO operational component is the Earth Observing System (EOS) Data and Operations System [EDOS]. The EDOS, using a complex network of antennas, computers, and communications systems, is responsible for acquiring, processing, and delivering instrument data to the ground for many of these missions—most importantly, the satellite and instrument data for the Terra, Aqua, and Aura platforms, referred to as the EOS "Flagship" missions.

The Data Journey: From Satellite to End-User

A growing international user community that includes scientists, educators, and federal, state, and local governments employs NASA's Earth-science data for research and applications on a regular basis. Moreover, all of the data are available to the public at no cost. The data are used in a variety of applications that benefit society, e.g., climate change research, disaster planning and response, natural resource assessment, and understanding Earth as an integrated system.

While data from Earth-observing satellites are used in myriad ways, many end-users are likely unaware of the complex journey that the data took to reach their individual workstations, laptops, or mobile devices.

While data from Earth-observing satellites are used in myriad ways, many end-users are likely unaware of the complex journey that the data took to reach their individual workstations, laptops, or mobile devices. Because NASA's Earth Science and Data Operations personnel are doing their job, many of these details will remain transparent, which is as it should be. Nevertheless, it is interesting to look behind the scenes and consider the journey that data make to get from the satellite to the end-user. The diagram shown in **Figure 2** can be a helpful reference in reading this section, as it represents this process graphically.

Transfer and Downlink: Getting the Data from the Satellite to the Ground

The journey begins at the moment the data are acquired by the satellite. A typical measurement is a radiance (the amount of radiation detected by the sensor) at a given time and location on the planet. In the case of Terra, these raw data, are sent to a

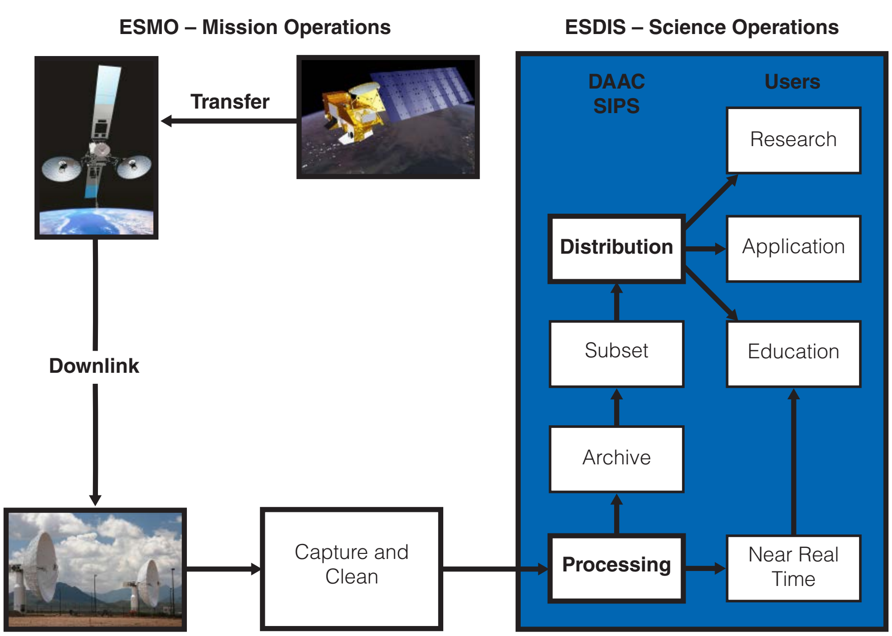

Figure 2. This figure illustrates Earth Science Data Operations functionality. The ESMO captures science and engineering data from the spacecraft and instruments, processes telemetry to Level-0 (raw satellite data). ESMO removes telemetry artifacts, creates sets of non-overlapping raw data as measured by the individual instruments over specific time intervals, and sends them to the designated Distributed Active Archive Centers (DAACs) and Science Investigator-led Processing Systems (SIPS) for further processing, archiving, and distribution to users. The DAACs and SIPS are the responsibility of the Earth Science Data and Information System (ESDIS) Project. **Image credit:** NASA

[2] See "Earth Science Mission Operations, Part I: Flight 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].

The overall goal of EOSDIS is to process, archive and distribute NASA Earth science data, from both NASA and other agencies, and related documentation that supports its origin and quality—information necessary for users to understand the overall provenance and data quality, and suitability for a given use.

member of NASA's Tracking and Data Relay Satellite System (TDRSS), which in turn sends the data to the ground for further processing and storage—see Figure 2. (Once the data reach the ground, they are referred to as Level-0.[3]) The process employs several backup capabilities to ensure that no data are lost. The EDOS has been recently upgraded with the ability to download data from non-NASA satellites such as those from the National Oceanic and Atmospheric Administration (NOAA) and the Japan Aerospace Exploration Agency (JAXA). Collaboration with these international space agencies is discussed further in a later section of this article.

Delivery: Data Reaches the Ground

Once the data have been received at ground stations, they are archived at the Earth Observing System Data and Information System (EOSDIS).[4] The system's overall objective is to process, archive, and distribute NASA's Earth-science data, and those from other agencies, and related documentation that supports its origin and quality—information necessary for users to understand the overall provenance and data quality and suitability for a given use. Toward that end, EOSDIS consists of processing facilities at science data centers distributed across the U.S.—see Figure 3—that serve hundreds of thousands of users around the world, by providing hundreds of millions of data files each year that cover every Earth science discipline. Not only does EOSDIS provide services for NASA satellites, it also provides archive services for data from NASA airborne missions (e.g. IceBridge[5]), field campaigns, and *in situ* measurement programs. These campaigns are an important component of NASA's Earth science research and highly complementary to satellite missions. The Earth Science Data and Information System (ESDIS) Project at GSFC manages these activities. The ESDIS performs these science operations within a distributed system of many interconnected nodes that include the Science Investigator-led Processing Systems (SIPS), and the discipline-specific Earth science Distributed Active Archive Centers (DAACs)—see **Table 1** on page 7 for a list of DAACs and their disciplines. The SIPS are also

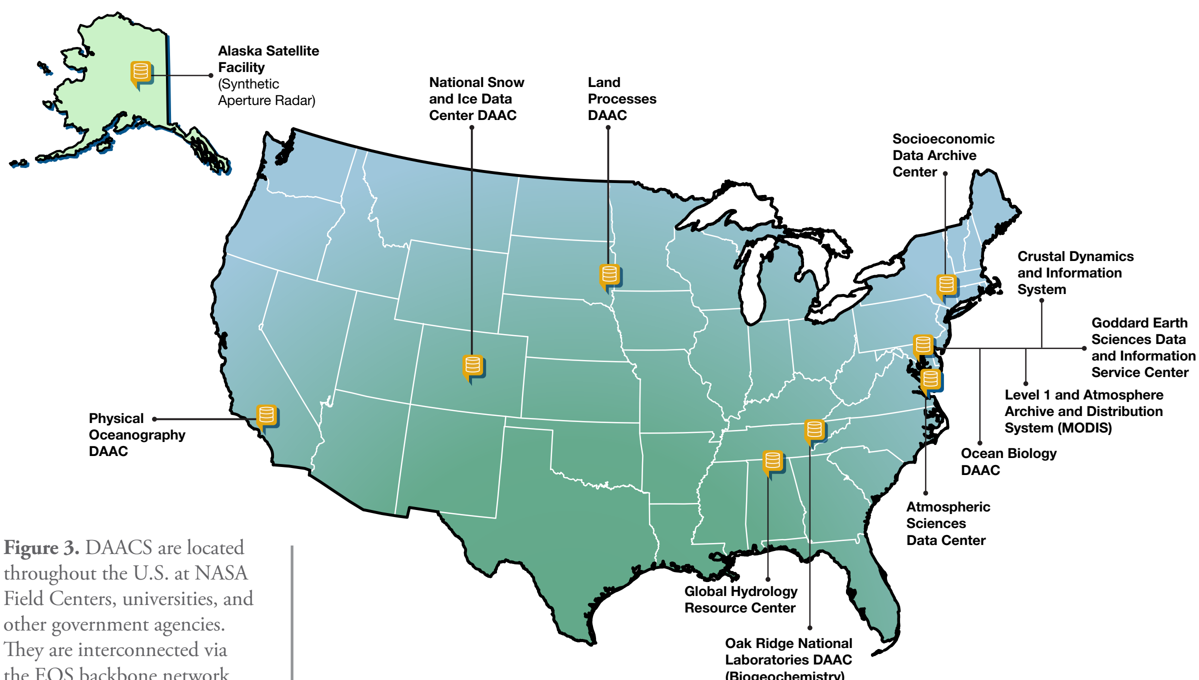

Figure 3. DAACS are located throughout the U.S. at NASA Field Centers, universities, and other government agencies. They are interconnected via the EOS backbone network and commodity Internet and research networks to allow further processing and distribution. The DAACs archive and distribute all of NASA's Earth-science standard data products along with tools for user access, interpretation, and analysis. **Image credit:** NASA

[3] NASA data Levels-0, -1,- 2, -3, and -4 (L-1 -2, -3, -4) are defined at *http://observer.gsfc.nasa.gov/sec3/ProductLevels.html*.

[4] The story of the EOS Data and Information System (EOSDIS) has been told in a two-part article, "EOS Data and Information System, Where We Were and Where We Are," that appears in the July–August 2009 and September–October 2009 issues of *The Earth Observer* [**Volume 21, Issue 4**, pp. 4-10 and **Volume 21**, **Issue 5**, pp. 8-15].

[5] Learn more about the IceBridge mission to measure changes in Greenland and Antarctica ice sheet volume at *http://icebridge.gsfc.nasa.gov*.

geographically distributed across the U.S. and are generally collocated with the satellite instrument principal investigator's (PI) or science team leader's facilities, which are housed at NASA Field Centers, universities, or other government agency sites. The DAACs have responsibilities for archiving, and distributing specific Earth-science data products and, in some cases, producing both data and ancillary products. Products from the SIPS are sent to appropriate DAACs for archiving and distribution, as discussed later.

Table 1. Description of NASA's Distributed Active Archive Centers (DAACs)

Alaska Satellite Facility (ASF) DAAC	
Location Fairbanks, AK **URL** *https://www.asf.alaska.edu*	ASF DAAC acquires, processes, archives, and distributes Synthetic Aperture Radar (SAR) data from polar-orbiting satellites and airborne sensors. The ASF provides online access to global SAR data (both from NASA and international agencies). The most recent data to be added is from ESA's Sentinel-1 mission.
Atmospheric Science Data Center (ASDC)	
Location NASA's Langley Research Center (LaRC) in Hampton, VA **URL** *https://eosweb.larc.nasa.gov*	The ASDC is responsible for processing, archiving, and distributing NASA's Earth science data in the areas of radiation budget, clouds, aerosols, and tropospheric composition. The ASDC supports over 50 projects and provides access to more than 1000 archived datasets, which were created from satellite measurements, field experiments, and modeled data products.
Crustal Dynamics Data Information System (CDDIS)	
Location NASA's Goddard Space Flight Center (GSFC) in Greenbelt, MD **URL** *http://cddis.gsfc.nasa.gov*	The CDDIS is NASA's data archive and information service supporting the international space geodesy community for over 30 years. The CDDIS serves as one of the core components for the geometric services established under the International Association of Geodesy (IAG), an organization that promotes scientific cooperation and research in geodesy on a global scale.
Global Hydrology Resource Center (GHRC) DAAC	
Location University of Alabama in Huntsville (UAH) **URL** *https://ghrc.nsstc.nasa.gov*	The GHRC DAAC is a joint venture of NASA's Marshall Space Flight Center and the Information Technology and Systems Center (ITSC) at UAH that provides an active archive of both data and analytical tools—particularly on hazardous weather, its governing dynamical and physical processes, and associated applications. GHRC focuses on lightning, tropical cyclones, and storm-induced hazards through integrated collections of satellite, airborne, and *in situ* datasets.
Goddard Earth Sciences Data and Information Services Center (GES DISC)	
Location GSFC **URL** *http://disc.gsfc.nasa.gov*	The GES DISC provides access to a wide range of NASA global climate data, concentrated primarily in the areas of atmospheric composition, atmospheric dynamics, global precipitation, and solar irradiance. The GES DISC provides tools for viewing and analyzing data from several heritage and Earth Observing System missions, including the NASA Flagships: Terra, Aqua, and Aura.
Land Processes (LP) DAAC	
Location U.S. Geological Survey's (USGS) Earth Resources Observation and Science (EROS) Center in Sioux Falls, SD **URL** *https://lpdaac.usgs.gov*	The LP DAAC ingests, processes, archives, and distributes data products related to land processes. These data are crucial to the investigation, characterization, and monitoring of biological, geological, hydrological, ecological, and related conditions and processes. The USGS archives and distributes Landsat data and derived products through the EROS Center *http://eros.usgs.gov*. The Center recently became a U.S. distribution point for Sentinel-3 data.

Table 1. Description of Distributed Active Archive Centers (DAACs) (Continued)

Level-1 and Atmosphere Archive and Distribution System (LAADS)	
Location: GSFC **URL:** *https://ladsweb.nascom.nasa.gov*	The LAADS specializes in quick access to Level-1 radiance and Level-2 and -3 atmosphere and land data products for the Moderate Resolution Imaging Spectoradiometer (MODIS) on both Terra and Aqua. LAADS also supports Level-1 and -2 atmosphere and land data products for the Visible–Infrared Imaging Radiometer Suite (VIIRS) on the Suomi National Polar-orbiting Partnership (NPP), as well as similar products from European satellites (e.g., Sentinel-3, ENVISAT).
National Snow Ice Data Center (NSIDC)	
Location: University of Colorado in Boulder, CO **URL:** *http://nsidc.org*	The NSIDC manages and distributes scientific data, creates tools for data access, supports data users, performs scientific research, and educates the public about the cryosphere. These data enable research that connects glaciers, ice sheets, ice shelves, permafrost, sea ice, soil moisture, and snow cover to climate change.
Oak Ridge National Laboratory (ORNL) DAAC	
Location: Oakridge, TN **URL:** *http://daac.ornl.gov*	The ORNL DAAC assembles, archives, and provides data and services for terrestrial biogeochemistry and ecological dynamics observations. Its goal is to understand terrestrial biogeochemical processes and to assess biogeochemical models. Available datasets consist of high-level satellite observations and data collected during field campaigns.These data include climate parameters, such as emission inventories and MODIS land products.
Ocean Biology Distributed Active Archive Center (OB.DAAC)	
Location: GSFC **URL:** *https://oceancolor.gsfc.nasa.gov*	The OB.DAAC serves as the DAAC for satellite ocean biology data from current and historical NASA missions and from partner space organizations. Ocean color data are used to study the biology and hydrology of coastal zones, changes in the diversity and geographical distribution of coastal marine habitats, biogeochemical fluxes and their influence in Earth's ocean and climate over time, and the impact of climate and environmental variability on the ocean.
Physical Oceanography Distributed Active Archive Center (PO.DAAC)	
Location: NASA/Jet Propulsion Laboratory in Pasadena, CA **URL:** *http://podaac.jpl.nasa.gov*	PO.DAAC provides data and related information, from multiple missions, pertaining to the physical processes and conditions of the global ocean, including measurements of ocean winds, temperature, topography, salinity, gravity, circulation, and currents.
Socioeconomic Data and Applications Center (SEDAC)	
Location: Columbia University in New York, NY **URL:** *http://sedac.ciesin.columbia.edu*	The SEDAC focuses on human interactions in the environment. Its mission is to develop and operate applications that support the integration of socio-economic and Earth science data and to serve as an "Information Gateway" between Earth sciences and social sciences. The data center has extensive assets related to population, sustainability, and geospatial data, and provides access to a large number of multilateral environmental agreements.

Processing: Checkout and First Data User

On arrival at the SIPS, the L-0 data are processed into the appropriate geophysical variables. The SIPS teams are then responsible for converting the geophysical variables to *EOS standard data products*[6]—see *How EOS Standard Data Products Are Created* on page 10. Once the science team is satisfied with its data quality, they are sent to the DAACs for long-term archiving and distribution to the world. In addition to the data, the science team provides sufficient documentation to explain the characteristics (i.e., location, spatial resolution, accuracy) of the data and how they were generated.

Distribution: Data Go Public

NASA is committed to ensuring that interested parties have ready access to Earth-science data to meet the challenges of climate research and environmental change as well as societal applications. Therefore, NASA promotes the interdisciplinary use of Earth-science data and supports a broad range of existing and potential user communities. Much of this activity is the responsibility of the DAACs. Their tasks include processing, archiving, providing descriptive documents and analytical tools, and distributing data from NASA's past and current Earth-observing satellites and correlative and research field measurement programs. NASA, through its DAACs, has more than 1.8 million Earth-science data users worldwide.[7]

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Each archive center serves one or more specific Earth-science disciplines and provides its user community with data products, data information (*metadata*), user services, and tools unique to its particular scientific discipline. Because each Earth-science discipline has its own unique approach to data retrieval, calibration and validation, and application, each of the DAACs provides details, with examples, on how to process, analyze, publish, or apply data.

To summarize, the DAACs' responsibilities are to serve a broad user community in the following areas:

- providing safe stewardship and archives for NASA's Earth-science data products;
- providing tools and services for users' data discovery and analysis;
- assisting in selecting and obtaining data;
- providing data-handling and visualization tools;
- notifying users of data-related news; and
- providing technical support and referrals as requested.

The following sections describe these responsibilities in more detail.

EOSDIS Tools: Making Data Accessible and Usable

As Earth science missions have evolved, various data discovery and analytical tools have been developed for searching, subsetting, and mapping, and particularly for visualizing their respective data products. Links to these tools can be found at *https://earthdata.nasa.gov/earth-observation-data/tools*. At this website, the user can find many tools that are data product- or mission-specific, or capable of operating across the DAACs' respective holdings. Examples of the more current and prevailing tools are described in the next four sections.

[6] An EOS standard data product is an official satellite data product produced by a designated principal investigator or science team leader. The algorithms used to produce each EOS standard data product undergo extensive peer review. Algorithm Theoretical Basis Documents (ATBD) exist for each data product, representing the formal peer-review mechanism. Further information on ATBDs can be found at *https://eospso.nasa.gov/content/algorithm-theoretical-basis-documents*.

[7] This is the number of distinct public users who received data product files, according to the EOSDIS FY2016 Annual Metrics Report.

How EOS Standard Data Products Are Created

Once the raw satellite data, L-0, and ancillary data* are stored at the Distributed Active Archive Centers (DAACs) they can be retrieved by the Science Investigator-led Processing Systems (SIPS)—normally just a few minutes after the data reach the ground from the satellite. The SIPS produce Level-1 (L-1) data products using instrument algorithms and calibration factors provided by the science team. Examples of L-1 data products are radiances (from spectrometers and radiometers) and signal return time (from radars and lasers). Instrument calibration products are generated to test instrument performance and check for trends that may be used to adjust the calibration factors. Parallel to this, the data are *geolocated*—the latitude and longitude where the data were obtained is identified and tagged to the data through time using the satellite's location and instrument pointing parameters.

Once L-1 data products are quality checked, they are processed to L-2. These are geophysical products, e.g., temperature, aerosol optical depth, precipitation, vegetation index, and ice sheet elevation, among many, many others. Again, L-2 data products are created using algorithms, usually developed by the instrument science teams using radiative transfer models that predict radiances from physical principles, and then iteratively compared to the measured radiances.

Nearly all science teams generate a L-3 data product. These data are L-2 geophysical variables that have been aggregated and projected onto a defined spatial grid over a defined time. For example, a MODIS† L-3 product is a global map of data (i.e., aerosol, vegetation index, cloud cover) that has been binned into a 1° x 1° (latitude x longitude) grid.‡ For this example, bins contain data taken over a single day, eight days, and one month. The process of *binning* involves various statistical techniques that help remove clouds and data spilling from adjacent grids that degrade the accuracy of the binned data.

Some instrument teams go one step farther, using similar L-2 data from several instruments that are carefully calibrated so that their data, after meticulous screening, can be stitched together over time to create a trend for a geophysical product.

There are also L-4 products, which are outputs from models that use the lower-level satellite data as input or results from analyses of lower-level data. The L-4 product could be constructed from data from multiple instruments.

Data quality influences the research quality or the cost of a user application; hence, ensuring data accuracy is an essential component of NASA's Earth-science mission. The various science teams spend considerable time and resources to ensure satellite data accuracy that is useful for science and beneficial applications. As the geophysical products are generated, a major parallel effort to calibrate and validate the data (commonly called *cal/val*) is under way. The cal/val process typically consists of comparisons with other measurements producing the same data product. These comparison (sometimes called *correlative*) measurements can result from data collected from the ground, aircraft, and even other satellite instruments that have already been carefully validated. Data refinement then results from iteration of L-1 and L-2 reprocessing using updated instrument calibration, correlative data, and improved geophysical algorithms. For most missions, the science team will use resources from SIPS to demonstrate the research utility of data and a pathway for their use in applications. To learn more about EOS Standard Data Products, visit *https://observer.gsfc.nasa.gov/sec3/EOSprod.html.*

*Ancillary data are data from sources other than the satellite that are combined with the data from the satellite to create certain higher-level products.

†MODIS stands for Moderate Resolution Imaging Spectroradiometer. The MODIS instrument flies on NASA's Terra and Aqua missions.

‡Each product may have its own binning time interval and geographical size. For more information on L-3 data using MODIS as an example, visit *http://modis.gsfc.nasa.gov/data/dataprod*.

Common Metadata Repository: A Map to Earth-Science Data

EOSDIS has developed systems that allow data users from around the world to easily search the entire EOSDIS data catalog of over 20 petabytes of data and find relevant data products in less than a second. A key component that makes this possible is the development of the Common Metadata Repository (CMR). *Metadata* are simply data that describe data, such as when and where the data were collected, the instrument used to collect the data and the instrument settings, how the data were processed (i.e., the data lineage or provenance), and the location associated with the product i.e., latitude and longitude. The CMR is a single, shared, scalable metadata repository that merges all current capabilities and metadata from the existing NASA Earth-science metadata systems of the Global Change Master Directory (GCMD) and the EOSDIS data collection, and allows expansion to enable new capabilities as users' needs to search and discover NASA data evolve.

Global Imagery Browse Services: A Global Database

The Global Image Browse Services (GIBS) provide quick access to over 200 full-resolution Earth-science imagery products covering every part of the world. Most imagery is available within a few hours after satellite overpass and data acquisition through the near real-time (discussed further below) LANCE system. The imagery archive is also being expanded to include additional historical products—spanning greater than 15 years—along with those from recently launched sensors. In total, there are over 240 trillion pixels' worth of imagery available that can be mapped on the users' web clients or geographic information system (GIS) software. GIBS features an intuitive interface, enabling interactive exploration of data, and supports a wide range of users that includes members of the research, applications, and outreach communities.

EOSDIS has developed systems that allow data users from around the world to easily search the entire EOSDIS data catalog of over 20 petabytes of data and find relevant data products in less than a second.

Worldview: A Broad-View Browser

Worldview[8] is the follow-on tool to the Rapid Response[9] system that dealt with MODIS data only. With this upgrade, the user is now able to explore the full range of GIBS imagery. Worldview provides the capability to interactively browse global, full-resolution satellite imagery and then download the underlying data. Many Earth-observation data products are updated within three hours of their measurement and then become available on Worldview. Users can select the data product and display it as a map with selected parameters. For example, users can select the date (current or past), then further select and zoom in on any event around the world. This capability supports time-critical application areas such as wildfire management, air-quality measurements, flood monitoring, tropical storm movement, and volcanic eruptions. Worldview can also be used on tablet and smartphone web browsers for mobile access.

Giovanni: Jump-Start Data Analysis

NASA's Geospatial Interactive Online Visualization ANd aNalysis Infrastructure (GIOVANNI) is a web-based tool that allows users to access, visualize, and analyze large amounts of Earth-science data without first having to download them.[10] The web interfaces are designed to be intuitive to enable data discovery, exploration, and analysis of global and regional datasets using standard formats. Giovanni portals are now providing geophysical model outputs in addition to the satellite data. Examples of visualizations include overlaid time-averaged parameters, time series plots of area-averaged parameters, difference plots, scatter plots with regression, and videos of time-dependent correlation maps of nearly every data product.

[8] Worldview is described and accessed at *https://worldview.earthdata.nasa.gov*. In addition, please read "Seeing is Believing: EOSDIS Worldview Helps Lower Barriers for NASA Earth-Observing Data Discovery and Analysis" in the May–June 2015 issue of *The Earth Observer* [**Volume 27**, **Issue 3**, pp. 4-8].

[9] Learn more about Rapid Response at *http://earthdata.nasa.gov/earth-observation-data/near-real-time/rapid-response*.

[10] Giovanni can accessed at *https://giovanni.gsfc.nasa.gov/giovanni.*

NASA's fleet of Earth-observing, low-Earth orbit satellites make near-global measurements once or twice a day. Various elements of EOSDIS process these measurements into EOS standard data products, using definitive geolocation and instrument calibration, within 8 to 40 hours of acquisition, and are capable of supporting high-quality research.

Near Real-Time Data Products

NASA's fleet of Earth-observing, low-Earth orbit satellites make near-global measurements once or twice a day. As has been described in this article, various elements of EOSDIS process these measurements into EOS standard data products, using definitive geolocation and instrument calibration, within 8 to 40 hours of acquisition, and are capable of supporting high-quality research. However, operational users and even some researchers often require data much more quickly for real- or near-real-time (NRT)[11] applications—e.g., numerical weather forecasting, monitoring natural hazards (i.e., floods and fires), agriculture (i.e., harvesting times, drought conditions, and freeze protection), and air quality (i.e., pollution and ultraviolet radiation exposure alerts).

Data delivered within three-to-five hours are generally referred to as *NRT data*.[12] These data can be produced by leveraging the existing EOSDIS processing facilities (see Figure 2). The key difference between the NRT and standard-processing data is the data used to determine geolocation. Standard products use definitive geolocation data (i.e., measured spacecraft attitude and ephemeris), provided once per day, whereas NRT products use predicted geolocation (based on orbital model calculations). If latency is not a primary concern, users are encouraged to use the standard science products that are created using the best available ancillary, calibration, and geolocation information.[13]

NRT data can come from individual processing groups such as the Ocean Biology Processing Group or the Precipitation Measurements Missions Team, both at GSFC. The majority of EOSDIS NRT data are produced by the SIPS and distributed through the Land Atmosphere Near real-time Capability for EOS (LANCE).[14] These data are primarily from the EOS Flagship instruments and provide a variety of Level-0 (L-0) to L-3 data products as well as global browse imagery.

An excellent example of NRT data is the Fire Information for Resource Management System (FIRMS).[15] MODIS and VIIRS[16] data are the principal sources of FIRMS data. The system delivers information on global hotspots and fire locations using standard formats for viewing on Google Earth within three hours of overpass by either instrument. Data products include active fires and thermal anomalies, in various locations that can be downloaded as maps and text files. A FIRMS tool that visualizes historic and current fire products and allows subsetting, locating, geographical layering can be found at *https://firms.modaps.eosdis.nasa.gov/firemap*. As mentioned earlier, the U.S. Forest Service directly accesses and customizes FIRMS data as well as other fire sources and posts results on their website (*https://fsapps.nwcg.gov/afm*) along with unique tools for assessing wildfire situations on regional and national scales.

In situations where on-ground data are limited or not available, some NASA partners (i.e., international government and non-profit agencies) use data from FIRMS to help them make tactical firefighting decisions. One such use is by Conservation International,[17] which supports improving management of protected areas, such as in Asia and the South American tropics. The FIRMS data are sent directly to

[11] The terms NRT, *expedited*, and *low-latency* are often used interchangeably. *Latency* describes the time between satellite observation and when the product is available to the end user.
[12] Examples of instruments and their NRT data products can be found at *https://earthdata.nasa.gov/earth-observation-data/near-real-time/download-nrt-data*.
[13] Further discussion of NRT applications can be found in "Summary of Workshop on Time-Sensitive Applications of NASA Data" on page 19 of this issue.
[14] More information about LANCE can be found at *https://lance.nasa.gov*.
[15] FIRMS is described in more detail at *https://earthdata.nasa.gov/earth-observation-data/near-real-time/firms*. In addition, please read "NASA FIRMS Helps Fight Wildland Fires in Near-Real Time" in the March–April 2015 issue of *The Earth Observer* [**Volume 27**, **Issue 2**, pp. 14-17].
[16] VIIRS stands for the Visible Infrared Imaging Radiometer Suite, which is an instrument flying on NOAA's Suomi National Polar-orbiting Partnership satellite, launched in October 2011.
[17] Find more information about Conservation International Firecast, visit *http://firecast.conservation.org/About*.

protected-area managers and forest- and fire-service organizations to assist in daily decisions that will have immediate conservation outcomes. One recipient of this information is the Bolivian forest service, which employs FIRMS data to enforce land-use policies and administer fines to land owners who violate those policies.

Metrics: Keeping Track of Performance

To provide guidance on the usability and performance of the DAACs and other NASA data sources, ESDIS maintains the ESDIS Metric System (EMS). The system collects and organizes various metrics from these sources and creates statistics on usage, on a daily basis, of DAAC products and services delivered via the Internet or managed in EOSDIS archives. NASA personnel can view detailed metrics to assess EOSDIS performance and trends. The ESDIS Project combines these metrics to provide a system-level overview of EOSDIS performance. This report provides snapshots of metrics as the combination of the individual DAACs and as a system. EMS metric data are reported annually and available to any user at NASA's Earthdata website (*https://earthdata.nasa.gov/about/system-performance/eosdis-annual-metrics-reports*).

The DAAC high-level metrics include the amount of data ingested, archived, and distributed annually. These are further subsetted into more-detailed metrics, which are sorted by satellite mission, instrument, science discipline, DAAC, user origin, and types (e.g., country, government, academic, industry)—examples are shown in **Tables 2a** and **2b**. EMS also tracks visitors, repeat visitors, top 20 domains, and top 20 countries. The number of data products delivered continue to grow as NASA's Earth science missions and end users grow—see **Figure 4** on page 14.

To provide guidance on the usability and performance of the DAACs and other NASA data sources, ESDIS maintains the ESDIS Metric System (EMS). The system collects and organizes various metrics from these sources and creates statistics on usage, on a daily basis, of DAAC products and services delivered via the Internet or managed in EOSDIS archives.

Table 2a. This table shows the number of files and the volume of data (terabytes) distributed in FY 16 sorted by DAACs—see Table 1 for list of DAACs and for expansions of acronyms used in Column 1.

DAAC	Files (Millions)	Volume (TBs)
ASDC	18.5	1,315.2
ASF	5.2	625.9
CDDIS	316.5	143.0
GESDISC	409.2	4,059.0
GHRC	3.9	8.8
LPDAAC	174.6	2,501.0
MODAPS	230.7	2,935.5
NSIDC	82.2	263.0
OB.DAAC	65.4	1,479.5
ORNL	31.6	71.7
PO.DAAC	93.0	481.3
SEDAC	5.8	2.9
LANCE	76.3	763.0
Total	1,512.9	14,649.9

Table 2b. This table shows the number of files and the volume of data (terabytes) distributed in FY16 sorted by instruments on the three EOS flagship missions: Aqua, Terra, and Aura

Mission	Instrument*	Files (Millions)	Volume (TBs)
Aqua	AIRS	6.4	459.5
	AMSR-E	6.6	66.4
	CERES	3.6	181.2
	MODIS	225.6	2,881.7
Terra	ASTER	8.1	273.6
	CERES	2.8	273.0
	MISR	1.9	132.9
	MODIS	237.9	3,085.0
	MOPITT	0.4	34.0
Aura	HIRDLS	0.1	0.9
	MLS	3.9	31.2
	OMI	10.0	218.8
	TES	0.2	6.9

* The instrument acronyms can be found in this article and/or at the individual instrument websites.

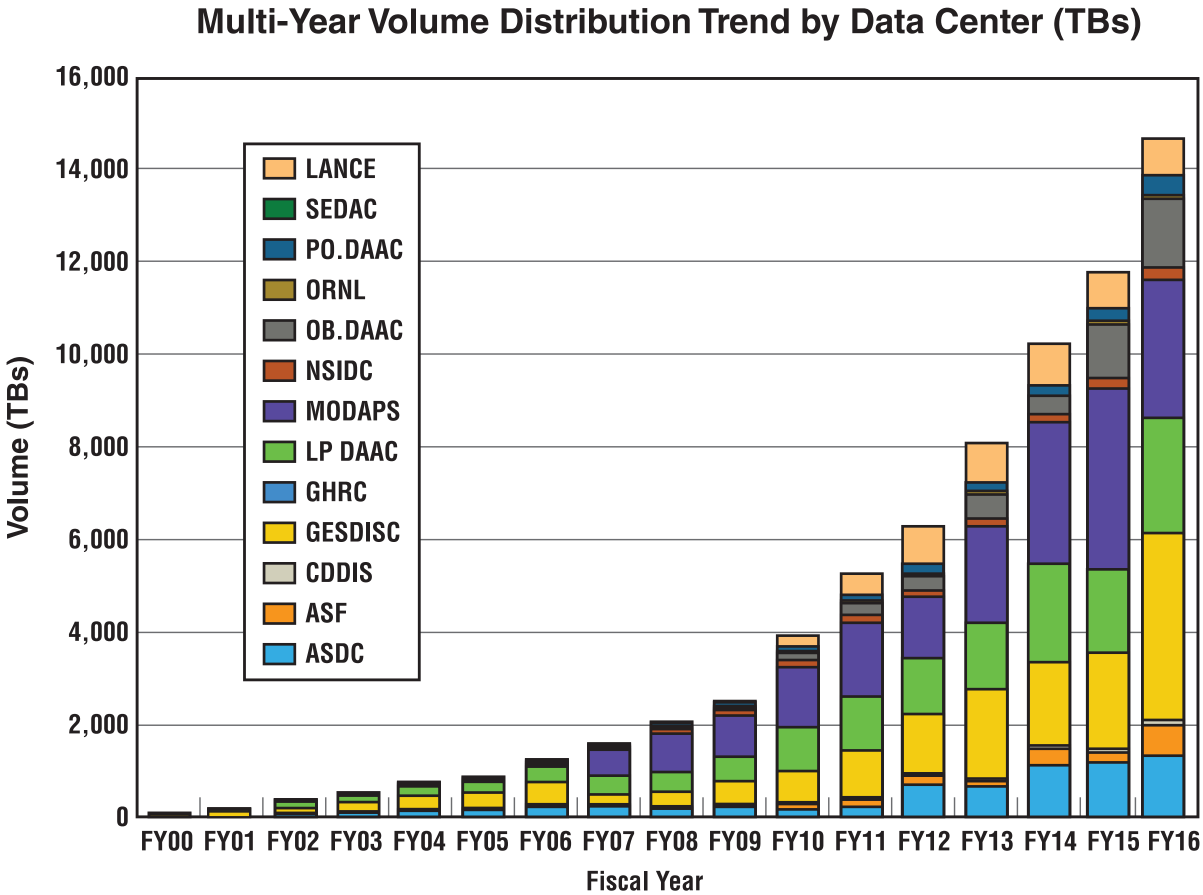


Figure 4. This chart illustrates the trend in the number of files distributed by each of the DAACs over the past 17 years in terabytes (TBs). The DAAC acronyms are defined in Table 1.

NASA encourages international users through announcements of opportunities, international working groups, formal Memoranda of Understanding that includes research and applications, and through mission partnerships.

Collaboration and Outreach

Collaboration with a variety of data users and other national and international space agencies is a high priority for NASA—particularly in the area of Earth-science data collection and distribution. NASA encourages international users through announcements of opportunities, international working groups, formal Memoranda of Understanding that include research and applications, and through mission partnerships.

Collaboration on Missions

Two of the largest mission partnerships are with the Japan Aerospace Exploration Agency (JAXA) and the European Space Agency (ESA). NASA also has formed partnerships with other European and North and South American space agencies, by way of data sharing and placement of mission instruments across platforms. Two examples of these partnerships include the Global Precipitation Measurement (GPM)[18] mission (with JAXA) and the Sentinel missions (with ESA).[19]

[18] The GPM mission centers on the deployment of the GPM Core Observatory and consists of a network, or constellation, of additional satellites. To learn more, visit *https://pmm.nasa.gov/gpm/constellation-partners*. The GPM Core Observatory has also been described in "GPM Core Observatory: Advancing Precipitation Instruments and Expanding Coverage" in the November–December 2013 issue of *The Earth Observer* [**Volume 25**, **Issue 6**, pp. 4-11].
[19] To learn more about ESA's Sentinel missions, visit *https://sentinel.esa.int/web/sentinel/home*. The Sentinels are among the missions described in "An Overview of Europe's Expanding Earth-Observation Capabilities" in the July - August 2013 issue of *The Earth Observer* [**Volume 25, Issue 4**, pp. 4-15].

GPM is a joint effort with JAXA, which provided the launch of the GPM Core Observatory. The primary mission objective is quantitative mapping of precipitation as the satellite carries an active and passive microwave instrument developed by both NASA and JAXA. GPM is a constellation of research and operational missions that conduct similar and related observations. GPM data and analytical and visualization tools can be found at the GES DISC—see Table 1.

NASA and ESA established a bilateral agreement to provide the U.S. research community access to data from the ESA Sentinels. ESDIS developed a dedicated gateway at GSFC that accesses data from the European Copernicus[20] data hub and passes the data to NASA's DAACs. To date, on a routine basis, data from Sentinels-1A and -1B and -3A are transferred from the gateway to the ASF and LAADS DAACs, respectively (see Table 1 for identifiers). Sentinel data[21] are available to all users through EOSDIS and its tools. The gateway provides an efficient platform for both NASA and ESA to distribute network and distribution loads in a way that maximizes collaboration, thereby benefitting Earth science research and applications, worldwide. **Table 3** lists all of the satellite missions supporting NASA Earth Science; **Figure 5** depicts the same information, graphically.

ESDIS has developed a dedicated data gateway between GSFC and the European Copernicus data hub that allows both NASA and ESA to distribute network and distribution loads in a way that maximizes collaboration, thereby benefitting Earth science research and applications, worldwide.

Table 3. List of current operational satellite datasets in EOSDIS.

Mission Name	Mission Long name	Agency*
Aqua	Aqua	NASA
Aura	Aura	NASA
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations	NASA
CYGNSS	Cyclone Global Navigation Satellite System	NASA
GPM	Global Precipitation Measurement	NASA, JAXA
GRACE	Gravity Recovery and Climate Experiment	NASA, DLR
OCO-2	Orbiting Carbon Observatory-2	NASA
SMAP	Soil Moisture Active Passive	NASA
SORCE	Solar Radiation and Climate Experiment	NASA
Terra	Terra	NASA
DMSP	Defense Meteorological Satellite Program	DoD, NASA, NOAA
DSCOVR	Deep Space Climate Observatory	NOAA, NASA, USAF
CATS on ISS	Cloud-Aerosol Transport System on the International Space Station	NASA
SAGE III on ISS	Stratospheric Aerosol and Gas Experiment III on International Space Station	NASA
GCOM-W1	Global Change Observation Mission - Water	JAXA, NASA
Jason-3	Altimetry Follow-on/Jason-3	NOAA, EUMETSAT, NASA, CNES
OSTM/Jason-2	Ocean Surface Topography Mission/Jason-2	NOAA, EUMETSAT, NASA, CNES
Sentinel-1	Sentinel-1 (1A and 1B)	EU-funded mission (ESA)
Sentinel-3A	Sentinel-3A	EU-funded mission (ESA)
Suomi-NPP	Suomi National Polar-orbiting Partnership	NOAA, NASA, DoD

*Undefined Acronyms in Table in Order of Occurrence: DoD–Department of Defense; NOAA–National Oceanic and Atmospheric Administration; USAF–U.S. Air Force; JAXA–Japan Aerospace Exploration Agency; EUMETSAT–European Organisation for the Exploitation of Meteorological Satellites; CNES–Centre National d'Études Spatiale [French Space Agency]; EU–European Union; ESA–European Space Agency.

[20] Copernicus is the European system for monitoring the Earth from satellites; learn more at *http://copernicus.eu*.

[21] Sentinels-1 and -3 primarily measure land, ocean, and ice properties and are complementary to NASA's Terra and Aqua and the NASA/NOAA Suomi National Polar-orbiting Partnership missions.

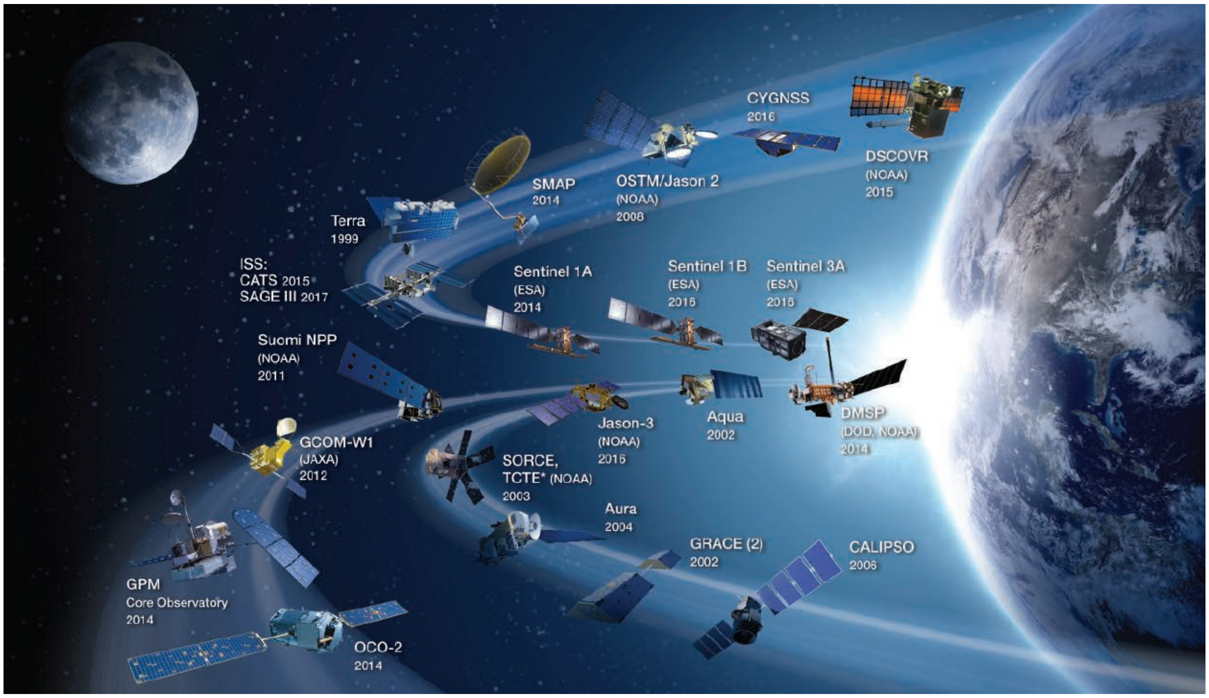


Figure 5 EOSDIS is connected to most—but not all—NASA missions through the Distributed Active Archive Centers (DAACs), which are responsible for archiving and distributing the data. Shown here are the missions that specifically use ESDIS resources. This includes a subset of the NASA missions depicted in Figure 1 as well as several international and interagency missions as defined in Table 3. This diagram does not represent the orbital tracks of each mission or the groupings of satellites. **Image credit:** NASA

Collaboration on Information Technology

NASA also collaborates internationally on science data-system development. An example is the Working Group on Information Systems and Services (WGISS), a subsidiary group of the Committee for Earth Observing Satellites (CEOS) that provides a venue for collaboration in the development of data systems and services that manage and distribute Earth-science data. NASA and other space agencies are able to demonstrate prototype systems that span a full range of information technology systems, including hardware and software, with an emphasis on interoperability of data across missions and Earth-science disciplines.

NASA also shares its data capabilities with the general science and applications communities via the Earth Science Information Partners (ESIP)—*http://www.esipfed.org.* ESIP is a community-driven organization that advances the use of Earth-science data through collaboration on topics such as data stewardship, technology, data interoperability, and applications areas such as disaster response, climate research, energy use, and agriculture productivity. ESIP partners include federal data centers, government research laboratories, research universities, educational resource providers, technology developers, and various nonprofit and commercial enterprises. ESIP initiatives and collaborations have resulted in the development of standards and best practices that make data more discoverable, accessible, and usable by scientists, decision-makers, and the public.

User Outreach

ESDIS has actively sponsored user outreach since the start of the EOSDIS program. This outreach includes a variety of printed materials and multimedia products, which enable users to find, access, and use NASA Earth-science data products. In addition to providing overviews of data from NASA Earth-science missions, specialized fact sheets feature data-product accessibility information, formats, analytical tools—described earlier—and other data services from the 12 DAACs by way of regular newsletters to keep users up to date. Hundreds of users regularly attend ongoing EOSDIS webinars focusing on current data issues. These virtual forums allow participants to interact with each other and have DAAC representatives answer questions in real time. These webinars can be found on the NASA Earthdata *YouTube* channel at *https://www.youtube.com/watch?v=AJQ3m3E8SCY*. ESDIS and the DAACs also use social media, such as Facebook and Twitter, to provide additional outreach channels.

New Developments: Exploiting Cutting-Edge Technology

The ESDIS continually strives to improve EOSDIS capabilities based on user needs by careful monitoring of its metrics (i.e., EMS), conducting user surveys, learning from NASA advisory committees, and application workshops, user feedback, and help tickets. Ongoing development includes improving visualization tools that are interoperable across the DAACs and ensuring use of open source as new software is developed. The success of these developments requires adherence to standards, best practices, and common data management across the EOSDIS. ESDIS has been a leader in network development with an eye toward increasing capacity and reducing costs. The system is well positioned to support new missions and the increasing demand for Earth-science data products. Provided below are two examples on how EOSDIS achieves some of these goals.

Big Data and Cloud Technology

The ESDIS project is currently evaluating commercial, cloud-based storage systems for core EOSDIS capabilities that center on satellite data ingest, archive, management, and distribution. The prototypes being examined will assess the advantages, risks, and costs associated with using commercial cloud environments. A two-year prototyping effort is underway that involves the DAACs and other stakeholders. The evaluation will include defining requirements, establishing capabilities, and determining cost-benefits for the user community. A cloud-based system would take advantage of the EOSDIS common metadata repository, likely employ OPeNDAP[22] services, and certainly encourage the user community to examine how to take advantage of possible architectural changes from the existing system.

Data Preservation

ESDIS also works with the DAACs and other partners on data preservation. As Earth-science data volumes continue to grow—with the increasing demand for monitoring and analyzing long-term changes of environmental parameters—data from the past must be preserved and plans made to preserve future data holdings. This task becomes more important in light of the over 50 years' worth of data currently available in Earth-observation archives around the world—and the increasing demand for monitoring long-term variations of environmental parameters. In order to achieve this goal, several factors need to be considered, such as technology assessments, media management, environmental control, data migration and storage refresh, multiple-copy strategy, physical security, access, and archival facility standards. ESDIS created the *NASA Earth Science Data Preservation Content Specification* document[23] that provides guidance on what data, documentation, and related information should be preserved. Several NASA missions have used this specification checklist as part of the data preservation process during satellite decommissioning while the science teams are still assembled. These requirements span a satellite instrument's full mission implementation, from prelaunch calibration to creation of science data software tools. ESDIS also invests in rescuing datasets from many older missions, i.e., the Nimbus series,[24] and the Heat Capacity Mapping Mission[25] that used a variety of obsolete media.[26] Once recovered, the data are retrievable from the EOSDIS and can be analyzed with existing tools.

"Building on the success of the past 25 years of data management, EOSDIS is all set to make significant progress providing new levels of service and data support to NASA's Earth-science missions, further enabling progress in Earth science."

— Jeanne Behnke *[GSFC—Deputy Project Manager for Operations for the ESDIS Project]*

[22] OPeNDAP is a software protocol that simplifies all aspects of scientific data networking. To learn more, visit *https://www.opendap.org.*

[23] The document can be found at *https://earthdata.nasa.gov/standards/preservation-content-spec*.

[24] To learn more, read "Nimbus Celebrates Fifty Years" in the March–April 2015 issue of *The Earth Observer* [**Volume 27**, **Issue 2**, pp. 18-31].

[25] The Heat Capacity Mapping Mission was launched in 1978 and was the first of a series of Applications Explorer Missions (AEM). The mission's objective was to provide comprehensive, accurate, high-spatial-resolution thermal surveys of the surface of the Earth.

[26] To learn about more examples of "rescuing" old data, read "Dark Data Rescue: Shedding New Light on Old Photons" in the May–June 2013 issue of *The Earth Observer* [**Volume 26**, **Issue 3**, pp. 4-10].

EOSDIS brings nearly 11,000 NASA Earth-science data products to 1.8 million users worldwide, users involved in every Earth-science discipline—at no cost.

Summary

This is the second of two articles on satellite flight and data management, where the first detailed satellite mission operations. This article described how EOSDIS brings nearly 11,000 NASA Earth-science data products to 1.8 million users worldwide, users involved in every Earth-science discipline—at no cost. The main function of EOSDIS is to process and distribute data from NASA and other agencies' satellites, as well as NASA's airborne, field campaign and *in situ* programs, in a format useful for scientific research, environmental management, policy development, and the emerging area of NRT data for the applications community. The number of NASA data users have grown significantly, where amounts of data distributed has increased by a factor of 15 over the last 10 years.

The core of EOSDIS is the network of DAAC facilities that process, archive, and distribute Earth-science data. In addition, DAACs provide tools and services for discovery and analysis, and technical support to a variety of users, and also provide notification of data updates and related news. ESDIS strives to better serve the data-provider science team as satellite instruments grow in sophistication. ESDIS is also well positioned to improve network efficiency and support additional capacity as demand surges for products from ongoing and planned satellite missions. ■

Undefined Acronyms Used in Editorial and Table of Contents

CLARREO	Climate Absolute Radiance and Refractivity Observatory
CYGNSS	Cyclone Global Navigation Satellite System
DLR	Deutsche Zentrum für Luft- und Raumfahrt [German Aerospace Center]
GFZ	GeoForschungsZentrum [German Space Agency]
KDP	Key Decision Point
LaRC	NASA's Langley Research Center
MSFC	NASA's Marshall Space Flight Center

Summary of the Workshop on Time-Sensitive Applications of NASA Data

Diane Davies, Science Systems and Applications, Inc./Trigg-Davies Consulting Ltd., diane.k.davies@nasa.gov
Molly Brown, University of Maryland, College Park, mbrown52@umd.edu
Kevin Murphy, NASA Headquarters, kevin.j.murphy@nasa.gov

Introduction

A workshop on Time-Sensitive Applications of NASA Data was held at NASA's Langley Research Center (LaRC), September 27-29, 2016, to identify, coordinate, and focus attention on societally relevant applications with time-sensitive, low-latency data needs—see *What do we mean by low latency?,* below. The meeting, supported by NASA's Science Data System Program and NASA's Applied Sciences Program, was the first time a group of NASA data users, producers, and scientists gathered to discuss the broad needs of time-sensitive science applications. There were 104 participants at the two-and-a-half-day meeting; the majority of participants (77) were from NASA, with the remainder made up of representatives from academic, government, nongovernment, and private institutions. For more information on the meeting, visit *https://wiki.earthdata.nasa.gov/display/EM/NASA+NRT+Workshop*.

The objectives of the workshop were to:

- describe and characterize the existing NASA low-latency Earth-science data portfolio;
- determine what additional NASA low-latency data are needed;
- determine which low-latency datasets could be provided in the coming decade;
- describe the processes required to enable acquisition of such datasets; and
- articulate the issues and challenges of low-latency data acquisition and management.

The pathway to achieve these objectives included plenary sessions and breakout meetings. Workshop participants described what low-latency Earth-observation data and products are available currently and what will be available from new sensors in the near term (i.e., 5-10 years), sought ways to increase the discoverability and usability of these products, and addressed how to engage new missions with regard to low-latency data.

NASA Headquarters Perspective

Michael Freilich [NASA Headquarters (HQ)—*Director of the Earth Science Division (ESD)*] highlighted that NASA ESD activities provide low-latency data and products when it involves small additional cost to existing processing. In doing so, NASA increases the societal value of its investment in Earth observations. However, the ESD is primarily a science organization and science and near real-time (NRT)

What do we mean by low-latency?

Data latency refers to the time between data acquisition and the time the data are available to the end user. The terms *near real-time* (NRT), *low-latency,* and *expedited* are often used interchangeably to refer to data that are made available more quickly than routine processing allows. In the context of NASA data, low-latency products are distinct from Earth Observing System (EOS) standard data products,* which provide an internally consistent, well-calibrated record of Earth's geophysical properties to support scientific research.

One key difference between some NRT and standard products is that the NRT geolocation may not be as accurate. This is because the standard products use the best knowledge of the spacecraft position and attitude which may not be available until after the NRT products are produced.

A second key difference applies to higher-level products that make use of ancillary data** as part of the algorithm. These Level-2 products have relaxed production rules to enable products to be produced with reduced processing times. By contrast, Level-2 products (e.g., fire, snow, and sea ice) that do not require ancillary data processing have the geolocation differences inherited from Level-0, but the code is identical to the ones used in standard operations.

*To learn more about EOS Standard Data Products, including the distinctions between the "Levels" please see *How EOS Standard Data Products are Created* on page 10 of this issue.
**Ancillary data are data from sources other than the satellite that are combined with the data from the satellite to create certain higher-level products.

research objectives outweigh support for NRT users when they are in direct conflict. Freilich charged the workshop participants to identify any significant populations of supporters and/or potential benefits from existing measurements and datasets that are missed because there is too much delay in providing ESD products.

Christine Bonniksen [NASA HQ—*Program Executive for ESD*] provided the NASA mission perspective on support for NRT data production. She said that the time to consider a low-latency data component in a new mission is when the mission is in its embryonic planning stages. Once the design process begins, changes in latency design should not be expected; that is not to say that latency cannot be improved during operations, but a funding source outside of flight programs will need to be identified.

Kevin Murphy [NASA HQ—*Program Executive for Earth Science Data Systems*] emphasized the importance of discoverability and usability of low-latency data. He encouraged workshop participants to leverage existing frameworks to raise the visibility of NASA low-latency data both within and outside of NASA—see **Table 1**. **David Green** [NASA HQ—*Disaster Applications Program Manager*] emphasized the importance of NRT data for time-sensitive applications and the disaster-relief community.

The Earth Science Data and Information System (ESDIS) Standards Office [ESO] assists the ESDIS Project in formulating standards policy for NASA Earth Science Data Systems (ESDS), coordinates standards activities within ESDIS, and provides technical expertise and assistance to standards related tasks within the NASA Earth Science Data System Working Groups (ESDSWG). To learn more about the ESDIS Standards Office, please visit *https://earthdata.nasa.gov/about/esdis-project/esdis-standards-office-eso*.

Low-Latency Data for Time Sensitive Applications

The workshop highlighted the importance of low-latency data for a range of applications and concluded that ongoing investment in development of low-latency data and products will enable increased societal benefit, particularly if outreach and data discoverability are improved. A selection of time-sensitive applications highlighted at the meeting is shown in **Table 2**.

Table 1: Common frameworks that knit together NASA's data and services.

Role	Implementations*
Data inventory	Common Metadata Repository (CMR)
Image repository	Global Imagery Browse Services (GIBS)
Data access	Open-source Project for a Network Data Access Protocol (OPeNDAP)
Data format standards	• Hierarchical Data Format (HDF) • Network Common Data Form (NCDF) • Earth Science Data and Information System (ESDIS) Standards Office
Collaborative development	Earthdata Code Collaborative

*HDF and Network Common Data Form (NCDF) are both existing data formats with details that can be easily accessed online.

Table 2. Applications and low-latency data highlighted at the workshop.

Application	**Speaker** [Affiliation]
Hazards Data Distribution System/NRT Landsat data	**Brenda Jones** [U.S. Geological Survey]
NRT data for Committee on Earth Observation Satellites (CEOS) and Group on Earth Observations (GEO)	**Stuart Frye** [NASA's Goddard Space Flight Center (GSFC)]
Advances in technology: improving delivery and accessibility of NASA's NRT data	**Mike Little** [NASA HQ]
Agricultural and drought monitoring	**Bob Tetrault** [U.S. Foreign Agricultural Service (FAS)] and **Chris Justice** [University of Maryland, College Park (UMD)]
Use of satellite data within weather decision support systems	**Brad Zavodsky** [NASA's Marshall Space Flight Center (MSFC), Short-term Prediction Research and Transition Center (SPoRT)]
Fire data and users	**Wilfrid Schroeder** [UMD] and **Karyn Tabor** [Conservation International]

Table 2. Applications and low-latency data highlighted at the workshop (continued).

Application	Speaker [Affiliation]
Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP)-derived NRT aerosols applied in Naval Research Laboratory (NRL) NRT data products	**Dave Winker** [LaRC] and **Kim Richardson** [Naval Research Laboratory (NRL)]
Low-latency datasets for time-sensitive applications under the U.S. Environmental Protection Agency (EPA) AIRNow Program: regional-to-global air quality.	**Jim Szykman** [LaRC]
NASA LaRC NRT satellite imager-based cloud property and clear sky temperature retrieval datasets	**Patrick Minnis** [LaRC]

Table 3: Presentations on sources of low-latency data.

Source	Speaker [Affiliation]
Land, Atmosphere Near Real-Time Capability for EOS (LANCE) data	**Chris Justice** [UMD—*LANCE User Working Group Chair*]
Direct Readout Laboratory (DRL)*	**Kelvin Brentzel** [GSFC]
Overview of the NRT data potential of the International Space Station (ISS)	**William Stefanov** [NASA's Johnson Space Center (JSC)—*Associate ISS Program Scientist for Earth Observations*]
Rapid Scatterometer (RapidScat) from the ISS	**Alex Fore** [NASA/Jet Propulsion Laboratory (JPL)]
Lightning Imaging Sensor	**Michael Goodman** [MSFC]
NRT data from field campaigns	**Don Sullivan** [NASA's Ames Research Center] and **Jay Al-Saadi** [LaRC]

*For more information, visit *https://directreadout.sci.gsfc.nasa.gov*.

Sources of Low-Latency Data

Low-latency data can be obtained from several sources within NASA including: the Land, Atmosphere Near real-time Capability for Earth Observing Systems (EOS) [LANCE],[1] Direct Readout stations[2], the International Space Station, and field campaigns—see **Table 3**. Other NASA low-latency or expedited data providers include NASA's Precipitation Processing System[3] and Distributed Active Archive Centers (DAAC) such as the Ocean Biology DAAC, the Atmospheric Science Data Center and the Physical Oceanography DAAC, and the Alaska Satellite Data Facility.[4]

[1] To learn more about LANCE, visit *https://earthdata.nasa.gov/earth-observation-data/near-real-time*.

[2] To learn more about Direct Readout, please read 2016 "Enabling Real-Time Earth Observations for Societal Benefits: The NASA Direct Readout Conference" in the November–December 2016 issue of *The Earth Observer* [**Volume 28**, **Issue 6**, pp. 22-30].

[3] For more information, visit *https://pps.gsfc.nasa.gov*.

[4] A complete table of DAACs appears on page 7 of this issue.

Inventory of NASA Low-Latency Data

A key output from the meeting was an inventory of all low-latency Earth science datasets currently available, as well as those that will be available from new sensors in the near-term (5-10 years). The inventory was created using an online spreadsheet; information includes the product name, data provider, expected latency, and a list of applications each product is potentially useful for. The inventory can be seen in full online at *http://tinyurl.com/nhmv9ky*.

Data Discoverability and Usability

Creating an inventory is one step towards making data more visible, but discoverability and usability are key to making the data more accessible. *Data discoverability* enables potential end users to determine what data are available and where they can be obtained. *Data usability* enables users to easily visualize or integrate the data into analysis tools to facilitate data use; this could be through making data available in easy-to-use formats such as geographical information system (GIS)-ready formats, making the data available for machine-to-machine access, or enabling users to interactively browse full-resolution imagery. NASA's Earth Observing System Data and Information System (EOSDIS) already has capabilities for discovery and visualization; these include the Common Metadata Repository (CMR), the Global Imagery Browse Services (GIBS), Worldview,[5] and the Earthdata Search client.[6]

Ana Prados [GSFC/University of Maryland, Baltimore County] highlighted the work of the NASA Applied Remote Sensing Training (ARSET) program, which provides training on how to access and use low-latency and standard NASA products. Surveys conducted at the end of ARSET training sessions highlight the popularity of Worldview—the EOSDIS client that enables users to interactively view full-resolution imagery, provided by GIBS, and to download the underlying data by linking to CMR.

Summary of Workshop Recommendations

Participants considered that significant populations would benefit from increased access to NRT data products through their own custom portals, improving access to NRT airborne measurements for atmospheric applications, and adding key NRT modeling products (e.g., data products from the Global Modeling and Assimilation Office) to Worldview and GIBS. They also recommended that NASA improve data discoverability by requiring that all NASA programs producing Earth-observation data register their products in the CMR. Consideration should also be given to registering in CMR both NASA applications products and non-NASA-funded operational products that use NASA data. Where feasible, imagery should also be added to GIBS to enable visualization.

[5] To learn more about CDR, GIBS, and Worldview visit *https://earthdata.nasa.gov/cmr, https://earthdata.nasa.gov/gibs,* and *https://worldview.earthdata.nasa.gov,* respectively. These three tools are also covered in "Earth Science Data Operations: Acquiring, Distributing, and Delivering NASA Data to Benefit Society" on page 4 of this issue.

[6] To learn more, visit *https://search.earthdata.nasa.gov.*

Improving data usability is as important to the community as accelerating data discoverability, therefore, the group recommended that NASA increase training opportunities and conduct case studies that enhance data usability. Many operational and applications users do not have the time or capability to process large files; they want products delivered via open-source, webbased mapping services that can be pulled directly into online web-mapping services or application-specific services. NASA already makes some datasets available as web-based mapping services, and is working to expand this capability further.

The uptake of and demand for NRT data continues to increase. Many of the satellites that currently provide NRT data products are aging (e.g., the EOS Flagships—Terra, Aqua, Aura.) and focus is shifting to creating new datasets that utilize data from newer missions [e.g., Suomi National Polar-orbiting Partnership (NPP)] in order to ensure NRT data continuity for operational decision makers. With regard to new Earth-science missions, workshop participants recommended that new missions should survey user communities to determine the value of low-latency products; work together to determine the benefit of these products for society; and include an element of data latency in all solicited and directed missions to ensure that teams have an opportunity to explore the benefits of including low-latency data products in their mission concepts.

Conclusion

The material presented at this workshop makes it clear that NASA successfully leverages existing systems to provide low-latency ESD data at little extra cost to the standard processing, search, and delivery systems. Looking to the future, representatives from NASA HQ agreed to continue this approach and consider additional low-latency datasets from new missions where large populations of supporters would significantly benefit from their delivery. Doing so will ensure that NASA continues to increase the societal value of its investment in Earth observations for many years to come. ■

2016 CLARREO Science Definition Team Meeting Summary

Amber Richards, Science Systems and Applications, Inc., amber.l.richards@nasa.gov
Bruce Wielicki, NASA's Langley Research Center, b.a.wielicki@nasa.gov
Rosemary Baize, NASA's Langley Research Center, rosemary.r.baize@nasa.gov

Introduction

The tenth meeting of the Climate Absolute Radiance and Refractivity Observatory (CLARREO) Science Definition Team (SDT) was held at the National Institute of Aerospace (NIA) in Hampton, VA, November 29-December 1, 2016. Over 30 investigators participated in the meeting, which comprised 26 presentations. Attendees were from NASA Headquarters (HQ), NASA's Langley Research Center (LaRC), NASA's Goddard Space Flight Center (GSFC), NASA/Jet Propulsion Laboratory (JPL), University of Wisconsin, Harvard University, University of Michigan, Lawrence Berkeley National Laboratory, Science Systems and Applications, Inc., McGill University (Canada), U.S. Geological Survey (USGS), and Imperial College London (U.K.).

The attendees discussed progress made on the CLARREO Pathfinder (CPF) Mission, which will fly a Reflected Solar (RS) instrument onboard the International Space Station (ISS) in the 2020 timeframe; received reports on science, project, and engineering progress for the Infrared (IR), RS, and Radio Occultation (RO) instruments; explored new efforts in support of NASA's Applied Sciences Program; and relayed the status of international collaboration efforts for CLARREO.

A few of the highlights from the presentations given at the meeting are summarized herein. Many of the presentations can be viewed online at *https://clarreo.larc.nasa.gov/events-STM2016-11.html*.

Session Topic Highlights

Provided here are highlights from a few of the presentations from the Fall 2016 meeting.

NIST Developments in Support of CLARREO Reflected Solar Instrument

Joe Rice [National Institute of Standards and Technology (NIST)] focused on three areas in which NIST has made progress in support of CLARREO's RS instrument.

1. *Exploring new approaches to Absolute Cryogenic Radiometer (ACR)-based calibrations.* The Spectral Irradiance and Radiance Responsivity with Uniform Sources (SIRCUS) is a reference facility for the calibration of detectors for spectral irradiance responsivity and spectral radiance responsivity across the ultraviolet (UV), visible, and much of the infrared spectrum. All irradiance and radiance responsivity calibrations made in the SIRCUS facility are traceable to the Primary Optical Watt Radiometer (POWR)—the U.S. standard for optical power. The optical power scale is transferred either directly from POWR, or

Attendees at the 2016 CLARREO SDT Meeting held at the National Institute of Aerospace (NIA) in Hampton, VA. **Photo credit:** George Homich [LaRC] an absolute cryogenic radiometer that is directly traceable to POWR, to transfer detectors used in SIRCUS. SIRCUS relies upon tunable lasers, which require hand-tuning over much of the RS spectral range. This also means that someone must be present at all times when the POWR ACR is in use. As a result, NIST is searching for sources that can be tuned automatically, thereby reducing the labor involved and enables calibrations to be run overnight. The two sources they are considering include a supercontinuum source-Laser Line Tunable Filter (LLTF) and a kHz Optical Parametric Oscillator (OPO) system. The NIST team has discovered that LLTF leads to full spectral response, automation, and improved dissemination of the primary radiance scale. To date, the visible/near infrared response has been demonstrated and the team is moving toward demonstrating response in the shortwave infrared and the near-ultraviolet ranges.

2. *Establishing standards for the 1.7-micrometer to 2.5-micrometer region while improving the spectral standard for broadband sources.* Experience with the NIST SIRCUS facility has demonstrated that moving from source-based scales (traceable to primary standard blackbodies) to detector-based scales (traceable to low-temperature cryogenic radiometers), offers opportunities to reduce the uncertainties in disseminated standards. NIST proposes using LLTF combined with stable spectrographs to improve transferred irradiance uncertainty by a factor of 10.

3. *Using a bandpass correction algorithm as a possible means to improve the resolution of spectrographs and scanning monochromators*. The implication of implementing such an approach is that the resolution in a scanning instrument can be improved by reducing the pixel-to-pixel spacing—or *step-size*—with no loss of throughput. By extending stray-light correction algorithms, the spectral resolution of spectrographs and spectrometers can be enhanced.

Summary of the CLARREO Pathfinder Intercalibration Concept

Constantine Lukashin [LaRC] followed with a discussion of the CPF concept for inter-calibration using the Clouds and the Earth's Radiant Energy System (CERES) and Visible Infrared Imaging Radiometer Suite (VIIRS) sensors on the Joint Polar Satellite System (JPSS)-1 platform, currently scheduled for launch late in 2017. These sensors were selected because of their high significance and utility in Earth-climate observations. **Figure 1** illustrates how CPF's data will be matched with data from CERES and VIIRS. Discussion continued with a presentation from **Chris Currey** [LaRC] regarding data management plans for CPF, including leveraging the Multi-Instrument

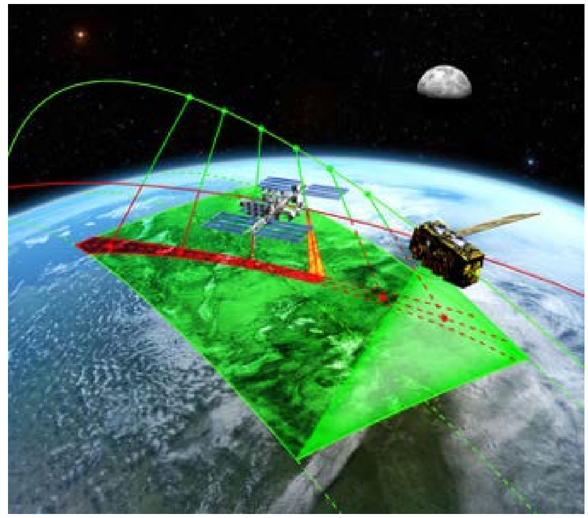


Figure 1. Demonstration of CPF's unique full-scan swath intercalibration capabilities with CERES and VIIRS sensors. CPF will demonstrate use of its improved accuracy (0.3%, k=1) to serve as an in-orbit reference spectrometer for advanced intercalibration of other key satellite sensors across the RS spectrum (between 350 and 2300 nm). **Image credit:** LaRC

Inter-Calibration (MIIC) System,[1] which is a distributed software framework that uses OPeNDAP[2] to access remote datasets. It allows for event prediction, data acquisition, and data analysis web services.

To see the agenda and full list of presentations from the CPF Inter-calibration Workshop, visit *https://clarreo.larc.nasa.gov/events-IW2016-11.html*.

Expected Accuracy of Decadal-Trends Retrieved from All-Sky IR Radiance Spectra

Bill Smith [University of Wisconsin (UW)-Space Science and Engineering Center] shared recent results from a simulation where his team used Climate Community System Model (CCSM) 100-year carbon dioxide (CO_2) doubling Observation System Simulation Experiment (OSSE) data to simulate CLARREO radiance spectra. The goal of this study was to determine how well decadal trends could be retrieved. Data included monthly mean atmospheric temperature and water vapor profiles and cloud and surface parameters for a ~1.5° grid from CCSM, Principal Component-based Radiative Transfer Model (PCRTM)-produced radiance spectra, 0.5° surface-emissivity data, and PCRTM cloud phase, optical depth, and particle size specified from CCSM cloud parameters. Smith then performed dual regression retrievals from monthly average CCSM grid point radiances for clear-sky and all-sky radiances.

[1] Learn more about MIIC at *https://earthdata.nasa.gov/community/community-data-system-programs/access-projects/miic*.

[2] OPeNDAP stands for Open Source Project for a Network Data Access Protocol; it is a software protocol that simplifies all aspects of scientific data networking. Learn more at *https://www.opendap.org*.

Smith's team found that linear regression retrievals from clear-sky hyperspectral IR radiances could provide accurate decadal trends (i.e., dependent climate-model-trained clear-sky results match the "Truth," which in this context means decadal trends produced by a 100-year climate model simulation). Independent, contemporary, clear-sky weather-profile training yields results similar (i.e., within 10%) to the dependent-sample results. For the case where the atmospheric profiles are uncorrelated with cloudiness—shown in **Figure 2**—they found that all-sky results are similar in accuracy relative to clear-sky results (i.e., ~ 1% difference) and

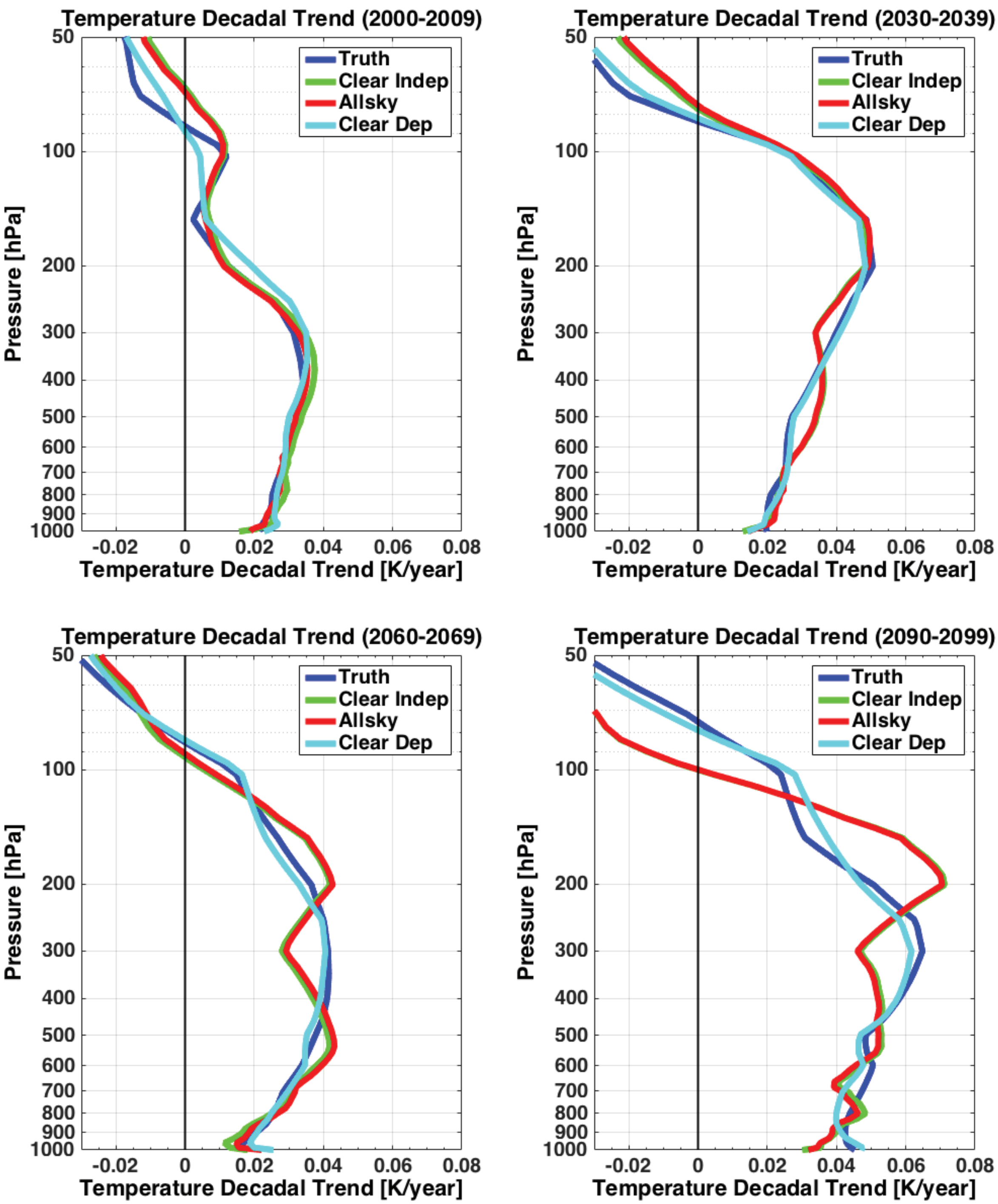


Figure 2. Examples of comparisons between decadal trends produced by a 100-year climate model simulation ("Truth"—*dark blue curve*) with decadal trends throughout the twenty-first century retrieved from simulated CLARREO spectral infrared radiance measurements, assuming: clear-sky conditions using a linear regression model trained with the climate model produced atmospheric conditions (Clear Dep—*light blue curve*); clear-sky conditions using a linear regression model trained with contemporary global weather observation atmospheric conditions (Clear Indep—*green curve*); and all-sky conditions using a linear regression model trained with contemporary global weather observation atmospheric conditions (Allsky Indep—*red curve*). **Image credit:** UW Space Science and Engineering Center

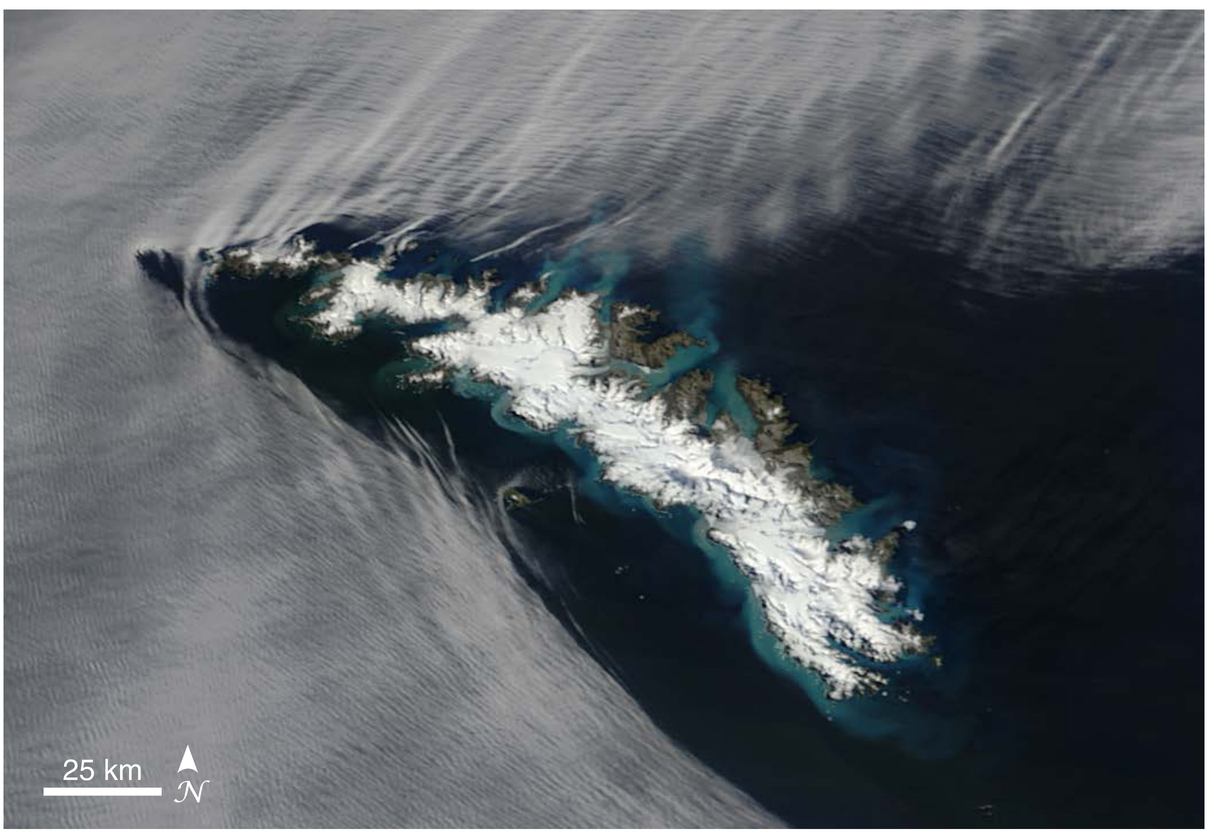
that multilevel clouds result in uncertainties that are similar to those of single-level clouds and have little impact on globally averaged decadal trends. These results demonstrate a new level of effectiveness in decadal change trend detection. This *average-then-retrieve* approach provides an alternative methodology to the classic *retrieve-then-average* approach. Future work includes comparing real Infrared Atmospheric Sounding Interferometer (IASI)[3] dual-regression all-sky retrieved decadal (2007-2016) temperature and water vapor profile trends with the climate model simulated IASI OSSE radiance-retrieved profile results for the same period.

Next Steps and Moving Forward

The meeting concluded with a discussion of the next steps that the CLARREO SDT needs to take to continue moving forward with the full CLARREO mission (IR and RS and RO) and with the CPF mission (RS only). The group discussed the economic value of higher-accuracy climate observation missions, ways in which NASA's Applied Sciences Program could work with CLARREO to identify opportunities to use CLARREO data for societal benefit, and the progress being made by the CPF team since passing their Mission Concept Review (MCR) on August 24, 2016. At the close of the meeting the group concluded that it would be very productive to host further discussions with members of the observation and climate modeling communities to discuss strategic planning efforts for observations needed to improve climate models and climate model predictions. As the team moves forward, the CPF activity will focus on the RS spectrum mission capabilities, while the CLARREO Pre-formulation activity will focus on the full infrared spectrum and RO capabilities. The team concluded that higher-accuracy observations remain a critical need for climate change observations.

The next CLARREO SDT Meeting is scheduled to take place May 17-19, 2017, at the Laboratory for Atmospheric and Space Physics (LASP) in Boulder, CO.

[3] IASI flies on the European Space Agency's MetOp series of satellites.



Like a ship carving its way through the sea, the South Georgia and South Sandwich Islands parted the clouds. The Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra satellite acquired this image on February 2, 2017. The ripples in the clouds are known as gravity waves. **Image credit**: NASA, Jeff Schmaltz, LANCE/EOSDIS Rapid Response. **Caption credit:** Pola Lem

Inaugural Multi-Angle Imager for Aerosols Science Team Meeting

Abigail Nastan, NASA/Jet Propulsion Laboratory, abigail.m.nastan@jpl.nasa.gov

Introduction

The Multi-Angle Imager for Aerosols (MAIA) investigation was selected on March 10, 2016, as one of two missions chosen in response to the third Earth Venture Instrument (EVI-3) solicitation, managed by NASA's Earth System Science Pathfinder (ESSP) Program Office at NASA's Langley Research Center (LaRC). MAIA's primary objective is to study how different types of airborne particulate matter (PM), differentiated in terms of both size and composition, impact human health. MAIA will use two pushbroom spectropolarimetric cameras to make radiometric and polarimetric measurements needed to characterize the sizes, compositions, and quantities of PM that contribute to air pollution. Researchers will combine MAIA measurements with population health records to better understand the connections between aerosol pollutants and health problems such as adverse birth outcomes, cardiovascular and respiratory diseases, and premature deaths.

The first MAIA Science Team Meeting was held at the Keck Institute for Space Studies at the California Institute of Technology (Caltech) on October 18-19, 2016. About 40 scientists, engineers, and managers participated in the meeting. **David Diner** [NASA/Jet Propulsion Laboratory (JPL)—*MAIA Principal Investigator*] led the meeting. He gave a review of the MAIA investigation strategy, and defined the meeting's principal objectives, which were to review the current status of the MAIA investigation and instrument planning, project organization, schedule, and upcoming milestones; foster interactions between the team members, who represent many different research disciplines and organizations; and establish top-level investigation requirements.

Program and Project Management Welcomes

The opening presentations focused on upper-level objectives and organizational roles and responsibilities. **Jim Graf** [JPL—*Deputy Director for Earth Science and Technology*] welcomed the Science Team and emphasized that MAIA will be the first JPL satellite remote-sensing mission specifically designed to benefit public health. **Diane Hope** [LaRC, Earth System Science Pathfinder (ESSP) Program Office—*MAIA Mission Manager*] described the responsibilities of NASA's ESSP Program Office, which include identifying the launch vehicle and host platform for MAIA (which is still to be determined), and helping to facilitate instrument success. **Hal Maring** [NASA Headquarters (HQ)—*MAIA Program Scientist*] and **Betsy Edwards** [NASA HQ—*MAIA Program Executive*] outlined the role of NASA Headquarters throughout the mission, including coordinating with the Science Team on assessments of the mission's progress. **Kevin Burke** [JPL—*MAIA Project Manager*] charted the mission's timeline and organization, explaining that MAIA is currently in the formulation phase (Phase A) with a projected launch date in the 2020-2022 timeframe. **Alberto Ortega** [JPL—*MAIA Business Manager*] covered the MAIA business office functions and near-term planning efforts.

Participants at the MAIA Science Team Meeting, held at the California Institute of Technology in October 2016. **Photo credit:** Michele Judd

The focus then shifted to more-technical matters. **John Pearson** [JPL—*MAIA Project System Engineer*] summarized the current status of the instrument design. He stated that the MAIA instrument consists of two cameras mounted side-by-side on a two-axis gimbal, explaining that the cameras will measure radiance in discrete spectral bands ranging from the ultraviolet through the shortwave infrared, and measure linear polarization in selected bands. The two gimbals will allow the cameras to view targets at multiple along-track angles covering ±67° from nadir, as well as point cross-track in order to observe targets not directly on the spacecraft ground track. The desired orbit of MAIA's host platform should allow for an average of three observations per week of each Primary Target Area (PTA), where large populations are exposed to particulate air pollution—to learn more, see *MAIA Primary Target Areas* on page 29.

Pearson reviewed progress on instrument design and trade studies since the proposal was selected. The fields of view of the two cameras have been narrowed in order to improve optical performance, but the swath width of approximately 400 km (~249 mi) (which may end up smaller or larger, depending on orbit altitude) is maintained by offsetting their boresights in a crossed-beam configuration—see **Figure**. The MAIA telescopes use mirrors to obtain broad spectral coverage, and the use of diamond-turned aluminum optics as an alternative to glass is being explored as a means of facilitating alignment of the optical system. As the likely orbit for MAIA will be sun-synchronous, a dark-side radiator and possible thermal shield have been added to enable cooling of the camera focal planes.

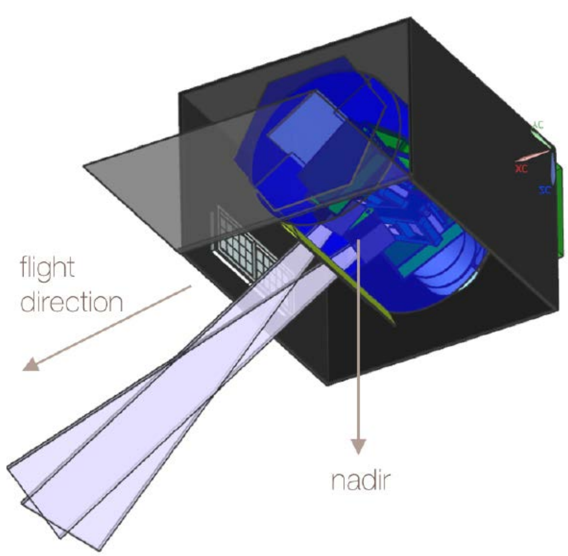


Figure. Conceptual schematic of the MAIA instrument, which consists of two spectropolarimetric pushbroom cameras mounted on a two-axis gimbal. This diagram depicts the configuration of the two cameras at the time of the team meeting, with crossed fields-of-view to maximize instrument swath width. The diagram depicts the gimbal position when pointed at a single along-track view angle. **Image credit:** Chaz Morantz

Science and Engineering Team Presentations

Instrument Design and Operation

MAIA leverages many years of experience at JPL with multiangular and polarimetric instruments, beginning with the Multi-angle Imaging SpectroRadiometer (MISR) instrument on NASA's Terra satellite, for which David Diner is also the PI. More recently, Diner led the development of the ground-based and first- and second-generation airborne Multi-angle SpectroPolarimetric Imagers (GroundMSPI, AirMSPI, and AirMSPI-2). The two airborne instruments fly aboard NASA's ER-2 high-altitude research aircraft, and have demonstrated the broad spectral range and polarimetric imaging technologies to be employed by MAIA.

Members of the instrument team gave overviews of their previous experiences with design and operation of MISR and AirMSPI and how those experiences benefit the MAIA investigation. **Carol Bruegge** [JPL] discussed radiometric calibration strategies and **Ab Davis** [University of Texas] discussed polarimetric calibration methods. **Padma Varanasi** [JPL] reviewed the flow of instrument operations from Science Team requests to the Instrument Operations Center, which will handle the observation scheduling and instrument monitoring. As a targeted instrument, MAIA will require more active prioritization of observations than a global instrument such as MISR. **Veljko Jovanovic** [JPL—*MAIA Data System Manager*] summarized the flow of data from raw instrument output to the highly processed PM maps. **Jeff Walter** [LaRC Atmospheric Science Data Center (ASDC)—*Lead Systems Engineer*] summarized how ASDC will manage the data production process for MAIA, which will leverage ASDC's experience with generating MISR products.

Epidemiology and Air Pollution

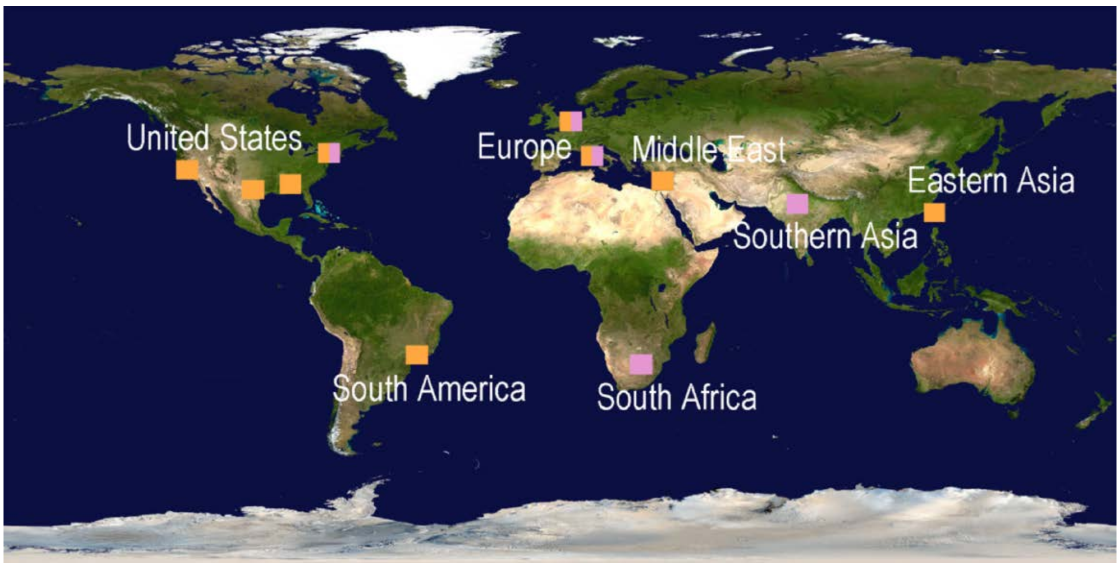
The MAIA Science Team includes many prominent epidemiologists interested in the health impacts of air pollution. For the benefit of the engineers and atmospheric scientists on the team, **Bart Ostro** [University of California, Davis] summarized how air pollution exposure data are used in acute 1-to-7-day), sub-chronic and birth outcome (1-to-9-month), and chronic (1-to-20-year and longer) epidemiology studies. **Yang Liu** [Emory University] reviewed his university's work on air pollution effects in the Southeastern U.S., and covered the acute and birth outcome studies for Atlanta, GA, that he plans to conduct as part of the MAIA investigation.

Joel Schwartz [Harvard University] discussed his research leveraging Medicare and Medicaid data in the U.S., and how MAIA could make use of these health data. **Sagnik Dey** [India Institute of Technology, Delhi] reviewed current studies of air pollution impacts in India. **Beate Ritz** [University of California, Los Angeles

MAIA Primary Target Areas (PTAs)

MAIA plans to study at least ten PTAs with sufficient population to enable the necessary statistical power for rigorous epidemiological studies. Eleven PTAs in North and South America, Europe, Africa, the Middle East, and Asia were identified as candidates in the MAIA proposal. Some of these areas are ideal for studies of chronic air pollution exposure, while others are more suited to studying health effects of short-term acute exposure (see map below). Likewise, PTAs in areas with well-established ground monitoring systems (such as the U.S. and Europe) will provide opportunities to calibrate the MAIA instrument, while other PTAs have been chosen to provide much-needed data in areas with few ground monitors. Depending on the selection of the host platform and its orbital characteristics, as well as the future availability of health records, some of these candidates or the specific metropolitan areas within them may change.

In addition to the PTAs, additional targets will be chosen for secondary aerosol and cloud science, calibration and validation, and for opportunistic events such as major wildfires or volcanic eruptions.



Locations of MAIA candidate Primary Target Areas (PTAs). Orange boxes indicate areas suitable for acute exposure studies, while pink boxes indicate areas intended for chronic exposure studies; areas with both colors are suitable for both types. **Background map credit:** NASA Visible Earth

(UCLA)] summarized the results of work on adverse birth outcomes associated with air pollution, and **Michael Jerrett** [UCLA] discussed the benefits of combining ground-monitor and satellite data to develop the most accurate exposure models.

Michael Brauer [University of British Columbia] summarized several current programs that could benefit from MAIA contributions, including the Global Burden of Disease study,[1] which seeks to understand global causes of mortality; the Prospective Urban and Rural Epidemiology air pollution (PURE-AIR) program,[2] which examines the effects of the highest recorded levels of air pollution; and the Effects of Low-Level Air Pollution: A Study in Europe (ELAPSE)[3] and Mortality-Air Pollution associations in Low Exposure environments (MAPLE),[4] both of which are concerned with the health effects of very low levels of air pollution.

[1] The Global Burden of Disease Study (GBD) is the most comprehensive worldwide observational epidemiological study to date. It describes mortality and morbidity from major diseases, injuries and risk factors to health at global, national, and regional levels. GBD is a collaboration of over 1800 researchers from 127 countries. Under principal investigator Christopher J.L. Murray, GBD is based at the Institute for Health Metrics and Evaluation (IHME) at the University of Washington and funded by the Bill and Melinda Gates Foundation.

[2] PURE-AIR is based at Oregon State University; find out more at *health.oregonstate.edu/labs/spatial-health/research/pure-air*.

[3] ELAPSE takes place in Europe and is coordinated by MAIA Collaborator **Bert Brunekreef** [Utrecht University]; learn more at *www.elapseproject.eu*.

[4] MAPLE takes place in Canada and is led by MAIA Co-Investigator **Michael Brauer** [University of British Columbia]; learn more at *www.healtheffects.org/research/ongoing-research/identifying-shape-association-between-long-term-exposure-low-levels*.

Application of Health Studies

Several government organizations involved in public health are also represented on the MAIA Science Team. **John Langstaff** [Environmental Protection Agency (EPA)] outlined how data from MAIA could help in interpreting variability in the health impacts of air pollution across urban areas and how EPA population exposure modeling can benefit such studies. **Pius Lee** [National Oceanic and Atmospheric Administration (NOAA), Air Resources Laboratory] explained his organization's air-quality forecasts, used daily to help schools, businesses, and individuals mitigate their health risks, and how MAIA might complement those forecasts.

Kembra Howdeshell [National Institute of Environmental Health Sciences, National Toxicology Program (NTP)] discussed how the NTP conducts systematic reviews of epidemiological studies to inform the public about the dangers of various toxic substances, including air pollution. **Judy Qualters** [Centers for Disease Control and Prevention (CDC), Division of Environmental Hazards and Health Effects] outlined how MAIA fits into the CDC's Air Pollution Science Agenda, an internal document released last year, especially the Climate and Health program (*http://www.cdc.gov/climateandhealth*), National Asthma Control program (*www.cdc.gov/asthma/nacp.htm*), and National Environmental Public Health Tracking programs (*ephtracking.cdc.gov/showHome.action*).

Particulate Matter Retrievals and Modeling

Much of the discussion at the meeting involved the process by which the MAIA instruments' measurements will be processed to create the final daily-averaged, speciated regional concentration products. **Veljko Jovanovic** began by explaining how the raw data will be geolocated and map projected. The team discussed tradeoffs in spatial resolution of the mapped data. **Larry Di Girolamo** [University of Illinois] outlined cloud-screening challenges and techniques and asked the team to carefully review the MAIA cloud mask requirements with an eye on how these requirements will impact MAIA science objectives.

Michael Garay [JPL] summarized the history of the aerosol retrieval process for MISR and AirMSPI,[5] covering the improvement of the MISR aerosol retrieval algorithm for MISR from 17.6 km (~10.9 mi) to 4.4 km (~2.7 mi) resolution, as well as how the polarimetric capabilities of AirMSPI provide more information about particle properties. **Olga Kalashnikova** [JPL] discussed current air pollution studies being done with AirMSPI, especially the Imaging Polarimetric Assessment and Characterization of Tropospheric Particulate Matter (ImPACT-PM) campaign studying particulate matter in California's Central Valley, of which she is Co-PI. **Feng Xu** [JPL] laid out the techniques to derive speciated aerosol concentrations currently being tested with AirMSPI, which involve correcting estimates from the Weather Research and Forecasting (WRF) Chemistry model [WRF-Chem][6] using AirMSPI-measured aerosol properties. He outlined how the choice of chemical transport model (CTM) for MAIA affects the retrievals, how uncertainties will be calculated, and the process for converting aerosol optical depth measurements to particulate matter concentrations in conjunction with the CTM. The team discussed the speciation of PM into sulfate, nitrate, organic carbon, black carbon, and mineral dust, and how ammonium and other species should be reported in the final product.

Several team members who have worked on similar modeling offered their viewpoints. **Alexei Lyapustin** [NASA's Goddard Space Flight Center] discussed his work on the Multi-Angle Implementation of Atmospheric Correction (MAIAC) product, which is assembled from aggregated MODIS[7] data gridded to 1-km (~0.6-mi) resolution. **Joel Schwartz** discussed his work using machine-learning techniques to calibrate satellite-measured aerosol optical depths on a daily basis using ground monitors. **Yang Liu** gave an overview of his proposed campaign of ground instrumentation to calibrate MAIA measurements specifically in Atlanta, GA (situated within a planned PTA), which would include one "core site" with highly accurate monitors, several "anchor sites" with permanent filter-based monitors, and many mobile sites, which might employ a car-based monitoring system.

Jun Wang [University of Iowa] compared the pros and cons of the WRF-Chem and the Goddard Earth Observing System (GEOS) Chemistry model [GEOS-Chem],[8] explaining that his team uses WRF-Chem for regional-scale studies and GEOS-Chem for global studies. The Science Team will need to choose a chemical transport model with which to produce its final mapped products. **Edward Hyer** [Naval Research Laboratory] discussed his work to improve estimates of wildfire smoke emissions for the U.S. Navy's global aerosol forecasts, which could be leveraged for MAIA by providing constraints on the aerosol retrieval

[5] A publications bibliography describing aerosol retrievals from MISR and AirMSPI is available on the MISR website at *http://misr.jpl.nasa.gov/publications/peerReviewed/index.cfm?CatID=40*.

[6] For more information about the WRF-Chem model, visit *http://ruc.noaa.gov/wrf/wrf-chem*.

[7] MODIS stands for Moderate Resolution Imaging Spectroradiometer, which flies on Terra and Aqua.

[8] 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 (GMAO). For more information, visit *http://acmg.seas.harvard.edu/geos*.

algorithm. **Randall Martin** [Dalhousie University] described the Surface Particulate Matter Network (SPARTAN), which installs PM speciation monitors near existing Aerosol Robotic Network (AERONET)[9] stations to constrain the relationship between aerosol optical depth and particulate matter concentration. MAIA plans to supplement the SPARTAN network with additional monitors.

Summary of Discussions

Throughout the meeting, the MAIA Science Team discussed the current open questions of the mission, including details of the instrument design, selection of the PTAs, and the top-level program requirements for mission success. Summaries of the discussions follow.

Instrument Design Trades

The current design for MAIA's spectral filters is based on AirMSPI-2, which has 12 spectral bands, of which 4 are polarimetric. The team as a whole discussed potential modifications for MAIA, including: optimization of the sensitivity to aerosol absorption in the ultraviolet and violet; inclusion of a band close to and longward of the 945-nm band to improve its utility for water vapor retrieval; and tradeoffs between the 1885-nm band and a prospective band at 1375 nm for cirrus cloud detection. **John Pearson** pointed out some of the engineering considerations that affect spectral band selection and noted that any performance improvements should not increase project costs or risks. Furthermore, **David Diner** stated that those decisions are needed by April 2017 to conform to the filter procurement schedule.

There was a discussion about tradeoffs between areal coverage and spatial resolution. Since the dimensions of the focal plane detector arrays are based on the AirMSPI-2 design and therefore fixed, the focal length of the optics determine the MAIA swath width and ground footprint sizes. Choosing the optimal focal length is complicated by the fact that the host platform's orbital altitude is not yet known. Within limits determined by engineering considerations and the desire to cover major cities within the candidate PTAs, the Science Team prioritized spatial resolution over swath. Depending on orbital altitude, the instantaneous footprint size is expected to be approximately 200 m (~656 ft) at nadir to allow for growth at off-nadir angles. Cities are chosen that have high population densities and that represent a variety of particle types and concentrations.

Because MAIA observations make use of a "step-and-stare" mode[10] of operation of the instrument's gimbal, the number of angles at which each target is observed also impacts the along-track length of the targets. A length exceeding 400 km (~249 mi) for a single target is possible with five angles (again, dependent on the exact orbital altitude), while observing at seven angles reduces this length to less than 300 km (~186 mi). These dimensions are sufficient to cover many of the cities being considered for targeting. The Science Team concluded that these questions should be explored interactively with the selection of the PTAs.

Primary Target Area Selection

The team discussed guidelines for final PTA selection after the host platform's orbit becomes known, which include the size of the encompassed human population, amounts and types of PM pollution present, availability of ground-based sunphotometers and PM monitors, and access to health records. After **Michael Brauer** presented results of the ELAPSE and MAPLE studies showing that PM exposure-response relationships (change in a given health outcome as a function of increase in PM concentration) are steepest at low levels of pollution, the team concluded that the PTAs should not be restricted to regions with elevated levels of air pollution but should represent a range of air pollution levels.

Top-Level Investigation Requirements

The MAIA System Requirements Review (SRR) in March 2017 is an upcoming milestone for the project, at which the top-level investigation requirements will be presented. The team discussed the draft Program Level Requirements Appendix (PLRA), an internal document that captures these Level-1 requirements for the mission. The threshold population needed for epidemiological studies within the PTAs was discussed, as was the required accuracy of the predicted PM levels in the MAIA data products.

Conclusion

At the conclusion of the meeting, three working groups were formed to study the current open questions: spectral band tradeoffs, PTA selection, and design of the aerosol and PM data products. The next MAIA team meeting will take place in 2017, after the SRR and prior to the project's Preliminary Design Review in late 2017 or early 2018. ■

[9] AERONET is a federation of ground-based remote sensing aerosol renote-sensing networks established by NASA and several French partners; to learn more please visit *http://aeronet.gsfc.nasa.gov.*

[10] A *step-and-stare* observation is taken by targeting the cameras at a certain area on the ground at a fixed gimbal angle, collecting observations as the satellite travels along track, and then retargeting the cameras to observe the same region from a different angle. In this manner multi-angular observations can be collected using the gimbal.

Ocean Surface Topography Science Team Meeting

Joshua Willis, NASA/Jet Propulsion Laboratory, joshua.k.willis@jpl.nasa.gov
Pascal Bonnefond, Laboratoire Géoazur, Observatoire de la Côte d'Azur, Centre National d'Études Spatiale, pascal.bonnefond@obs-azur.fr

Introduction

The 2016 Ocean Surface Topography Science Team (OSTST) Meeting was held in La Rochelle, France, November 1-4, alongside the Synthetic Aperture Radar (SAR) Altimetry Workshop,[1] and the International Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) Service [IDS] Workshop,[2] held in the same location on October 31 and October 31 – November 1, respectively, as part of the "New Era of Altimetry, New Challenges" symposium.

The primary objectives of the OSTST Meeting were to:

- provide updates on the status of the U.S-European Jason-2 and -3 missions;
- conduct splinter sessions on various corrections, altimetry data products, ocean science, and related activities; and
- present preliminary analyses of data from the altimeter on Jason-3, which was launched on January 17, 2016.

The meeting lasted three-and-a-half days to accommodate discussions during dedicated roundtables for each splinter session. A report of the meeting, along with all of the presentations from the plenary, splinter, and poster sessions, are available on the Archiving, Validation, and Interpretation of Satellite Oceanographic data (AVISO) website at *http://meetings.aviso.altimetry.fr*.

Status Report on Current Ocean Surface Topography Missions

Jason-3 was successfully launched from Vandenberg Air Force Base on January 17, 2016, aboard a Falcon 9 launch vehicle built by SpaceX. All of Jason-3's systems and instruments are operating nominally after a remarkably efficient start-up of the satellite. The radar was activated on January 19 at 16:12 GMT, and the first near-real-time data were delivered three hours later. On February 12, 2016, Jason-3 was maneuvered into position approximately 80 seconds behind Jason-2 where it spent six months in tandem formation with Jason-2 while the new data were evaluated relative to the leading spacecraft. In October 2016 Jason-2 was moved into an orbit with ground tracks halfway between the Jason-3 tracks (a so-called interleaved orbit). In addition, a five-day lag was introduced into the Jason-2 orbit, making its current orbit identical to the one flown by Jason-1. Based on the quality of the geophysical data records (GDR)[3] that have been generated to date, the OSTST recommended the immediate public release of the GDR products for Jason-3. This and other recommendations are described in the *Summary of Recommendations from the 2016 OSTST Meeting* section on page 34.

Launched in June 2008, Jason-2 continues to operate nominally in the interleaved orbit. All systems on Jason-2 are in good condition and the satellite is operating nominally after eight-and-a-half years in orbit. The cognizant agencies [Centre National d'Études Spatiale (CNES), European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), NASA, and the U.S. National Oceanic and Atmospheric Administration (NOAA)] have approved extending mission support through at least 2017. Jason-2 continues to collect data that meet all mission and Level-1 science requirements.

Opening Plenary Highlights

During the opening plenary session three keynote talks were given, in addition to some background information and a status report on a new NASA mission under development. These are summarized in this section.

Marta Marcos [University of the Balearic Islands, Palma, Spain] discussed progress in reconstructing long-term global sea level changes, explaining that this new global mean sea level (GMSL) curve is now more consistent with the historical Coupled Model

[1] SAR technology is beginning to allow radar altimeters to make higher resolution measurements, making this topic an important one for the future of altimetry.

[2] IDS is one of the important positioning systems aboard the Jason (and other) satellite altimeters.

[3] A geophysical data record (GDR) refers to a fully validated data product that uses precise orbital values and the best environmental/geophysical corrections. Used throughout this summary, the -C, -D, and –E nomenclature refers to different data product releases, each using updated processing techniques, to make the datasets more accurate and consistent across all of the missions.

Intercomparison Project Phase 5 (CMIP5)[4] modeling attempts especially for outputs between the 1930s and 1970s. He stated that acceleration in GMSL is stronger than in any other reconstruction and that recent rates of GMSL are higher than earlier recorded periods.

Thierry Penduff [Laboratoire de Glaciologie et Géophysique de l'Environnement, Grenoble, France] discussed the fingerprints of chaotic behavior[5] in ocean currents chaos and atmospheric forcing on both altimeter and *in situ* data and its observational consequences. These investigations provide the community with quantitative estimates of the chaos-related uncertainties associated with individual and integrated observational information, and of the observed part of observed signals that may be explained by atmospheric phenomena.

Angelica Tarpanelli [Research Institute for Geo-Hydrological Protection, National Research Council, Perugia, Italy] discussed the use of radar altimetry and its integration with other satellite sensors for river discharge estimation and forecasting. The integration of data from different sensors, including altimetry, represents an added value to the information derived from single-sensor data and widens the possibilities of increasing the accuracy of river-discharge estimates.

In addition to the three keynote presentations, **Lee-Lueng Fu** [JPL] presented a progress report on the Surface Water and Ocean Topography (SWOT)[6] mission, which will observe ocean surface topography at unprecedented spatial resolution but with moderate temporal resolution; it is scheduled for launch in 2021.

[4] CMIP-5 is the fifth phase of a project of the World Climate Research Programme (1995) that seeks to study the output of coupled atmosphere-ocean general circulation models (AOGCMs). CMIP provides a community-based infrastructure in support of climate model diagnosis, validation, intercomparison, documentation, and data access. This framework enables a diverse community of scientists to analyze GCMs in a systematic fashion, a process which serves to facilitate model improvement. Virtually the entire international climate modeling community has participated in this project since its inception. To learn more see *http://cmip-pcmdi.llnl.gov/cmip5.*

[5] Chaotic behavior refers to behavior that is so unpredictable as to appear random, owing to extreme sensitivity of initial conditions. Weather behaves this way and it is the chaotic nature of weather that prevents accurate forecasts of more than a week or so. Similar dynamics appear in the ocean and are the focus of this study.

[6] SWOT was identified as a *Tier 2* mission in the National Research Council's 2007 Earth Science Decadal Survey, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*, which provided the basis for the future direction of NASA's space-based Earth observation system. The mission brings together two traditional separate research areas to develop a better understanding of the world's ocean, terrestrial surface waters, and the interplay between them. The report can be downloaded from *www.nap.edu/catalog/11820/earth-science-and-applications-from-space-national-imperatives-for-the.*

Splinter Session Highlights

Following the opening plenary session, focused splinter sessions were held, named as follows:

- Application Development for Operations (called *Near Real-Time* splinter in previous meetings);
- Instrument Processing: Corrections (Troposphere and Ionosphere, Wind Speed, and Sea State Bias);
- Instrument Processing: Measurement and Retracking [SAR Mode and Low Resolution Mode (LRM)];
- Outreach, Education, and Altimetric Data Services;
- Precise Orbit Determination (POD);
- Quantifying Errors and Uncertainties in Altimetry Data;
- Regional and Global Calibration/Validation for Assembling a Climate Data Record;
- Science Results from Satellite Altimetry:

  - Current and past mean sea level observations;

  - From large-scale oceanography to coastal and shelf processes;

  - Two decades of continental water's survey from satellite altimetry - From nadir low-resolution mode to SAR altimetry, new perspectives for hydrology;
- The Geoid, Mean Sea Surfaces, and Mean Dynamic Topography; and
- Tides, Internal Tides, and High-Frequency Processes.

The narrative in the next two sections highlights two key results shared during the meeting that pertain to measuring sea level rise—a key application of Ocean Surface Topography measurements that is broadly relevant to society. Complete coverage of the results can be found at the AVISO website mentioned in the Introduction.

Precise Orbit Determination

Sea surface height is the primary measurement provided from satellite altimetry. The sea surface height is calculated as the residual between the range from the satellite to the ocean surface (measured by the radar altimeter) and the location of the satellite relative to the center of mass of the Earth (determined by the satellites many positioning systems). Since the launch of the Ocean

Summary of Recommendations from the 2016 OSTST Meeting

The OSTST adopted several official recommendations to the agencies regarding current and upcoming missions. These are summarized below. The full text of the recommendations can be found at *http://www.aviso.altimetry.fr/fileadmin/documents/OSTST/2016/OSTST_2016_Meeting_Report.pdf* .

The OSTST found that the quality of the official data product for Jason-3 was excellent and recommended that it be released for public use immediately.

The plan for Jason-2 was also discussed and the OSTST recommended that in October 2018, after two years in interleaved orbit, Jason-2 be moved from (where it best serves the oceanographic community, both operational and scientific), to a Long Repeat Orbit (LRO) where it will better serve to improve the resolution and accuracy of the mean sea surface, and marine gravity measurements. A specific orbit for the LRO mission was identified at an altitude that is 27 km (~17 mi) lower than its current 1336 km (~830 mi) altitude. The recommendation recognized that Jason-2 may need to be moved sooner if satellite health declines, but emphasized that data accuracy, latency, and availability requirements should be maintained in the LRO orbit, as long as the satellite is still viable.

The OSTST also stated that it was willing to accept an increased latency for the official GDR release of Jason-2 and Jason-3 data, in order to allow a more stable *wet path delay correction** over the long term. An external calibration performed by tilting the spacecraft and pointing the radiometer into space ensures that this path delay remains accurate and stable. The OSTST accepted the fact that relaxing the latency of the GDR delivery to a maximum of 90 minutes would ensure that at least two such calibrations were always possible, and ensure that the accuracy of the Jason measurements is high enough to measure globally-averaged sea level change.

Last year, the OSTST recommended that future altimetry missions should consider adding additional higher-frequency radiometer channels in order to improve coastal and inland water wet path delay corrections.** During the plenary session, the European Space Agency (ESA) announced the implementation of such a radiometer onboard Jason-CS/Sentinel-6*** with three additional channels (90 GHz, 130 GHz, and 166 GHz). Even if only experimental and nonredundant, the OSTST greatly appreciated this initiative.

On Jason-CS/Sentinel-6, there is a small probability that the external calibrator for the Advanced Microwave Radiometer (AMR) onboard, could fail in a position that renders the AMR unusable for the remainder of the mission. **Pierrik Vuilleumier** [ESA] presented this issue and stated that with all the efforts made, a very small likelihood (but nonzero) risk for in flight failure exists. However, the OSTST recognizes the importance of maintaining the climate record of sea level change. Because long-term stability of the AMR is required in order to achieve this, the OSTST recommends acceptance of the additional risk of loss of AMR functionality as reported by the project in order to improve long-term stability on Jason-CS/Sentinel-6.

* *Wet path delay* is a measure of the amount of water vapor in the atmosphere beneath the satellite. The more water vapor present, the longer it takes for the radar pulse from the spacecraft's altimeter to travel to the ocean surface and back. By knowing exactly how much water vapor is in the signal's path, together with the time it takes for the signal to bounce back, mission scientists can calculate the exact distance between the satellite and the ocean surface. This information along with the precise location of the spacecraft allows them to determine the height of the sea surface. For example, see *https://www.nasa.gov/mission_pages/ostm/multimedia/comp-20080730.html#.WOuc9hjlSel*.

** Aircraft observations have shown that high-frequency radiometer observations provide improved measurements of *wet-path delay* near land. See "2015 Ocean Surface Topography Meeting Summary" in the March–April 2016 issue of *The Earth Observer* [**Volume 28**, **Issue 2**, p. 17, first bullet in column 2].

*** Jason-Continuity of Service (CS)/Sentinel-6 is the next planned Ocean Surface Topography mission that aims to continue the high-precision ocean altimetry measurements in the 2020–2030 timeframe via two successive identical satellites (Jason-CS-A and Jason-CS-B). The Sentinel Missions are part of the European Space Agency's (ESA) Copernicus Programme. They are detailed at *http://m.esa.int/Our_Activities/Observing_the_Earth/Copernicus/Overview4*

Topography Experiment (TOPEX)/Poseidon mission in 1992, the accuracy of both components has improved steadily as corrections to both have improved. This OSTST meeting was dedicated largely to the task of evaluating the newly launched Jason-3 satellite, and to make sure that the record of sea level change remains well-calibrated and unbroken through the transition from Jason-2 to Jason-3. **Figure 1**, presented by **Frank Lemoine** [NASA's Goddard Space Flight Center (GSFC)], shows the agreement between Jason-2 and Jason-3 during the tandem phase when both satellites observed the same ocean, 80 seconds apart. With a root mean square (RMS) difference of just 1.2 mm (~0.05 in), the agreement between the two satellites is truly remarkable and the long-term record of sea level change remains intact.

Science Results from Satellite Altimetry

The two main scientific themes in the *Science Results from Satellite Altimetry: Current and past mean sea level observations* session addressed disagreements between historical reconstructions of sea level, and the estimate of acceleration in GMSL during the satellite altimetry era. **Phil Thompson** [University of Hawaii] presented a new study, which attempted to reduce the uncertainty and complexity of GMSL reconstructions and establishing a "likely range" of twentieth century rates of GMSL rise. He found that estimates above 1.85 mm/year (~0.07 in/year) and below 1.4 mm/year (~0.06 in/year) are highly unlikely given the best available tide gauge data—see **Figure 2**. While this does narrow the range, it does underscore the ongoing issues associated with estimating twentieth century GMSL.

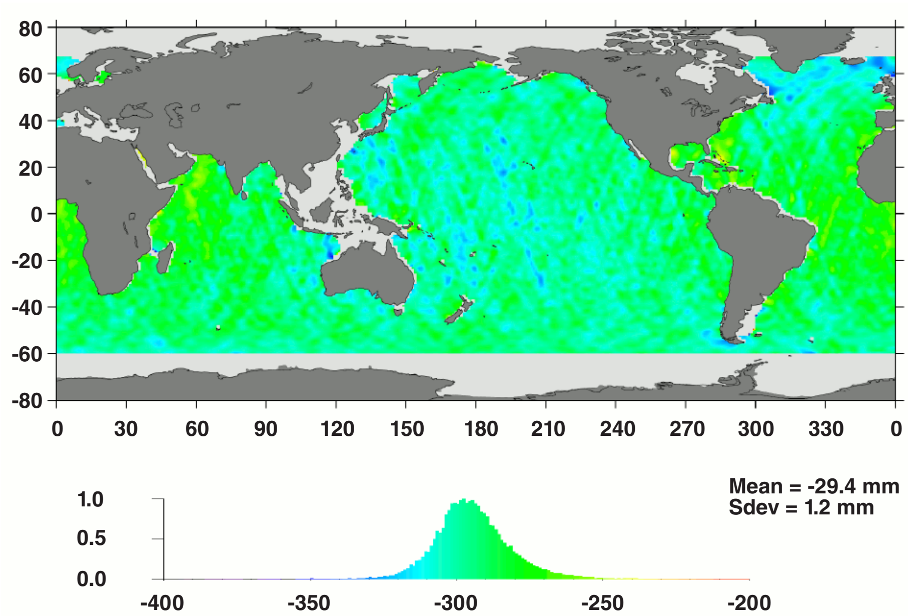


Figure 1. This map shows the difference between Jason-2 and Jason-3 observations of sea surface height from March-August of 2016, during the tandem mission when both satellites measured the ocean from the same location and at nearly the same time. The mean difference between the two is -29.4 mm (~-1.2 in); the RMS difference between the two is only 1.2 mm (~0.05 in). The graph shows the frequency distribution of the differences between the two satellites. This means the long-term record of sea level change will remain intact and highly accurate as Jason-3 takes over observations from Jason-2. **Image credit:** Frank Lemoine

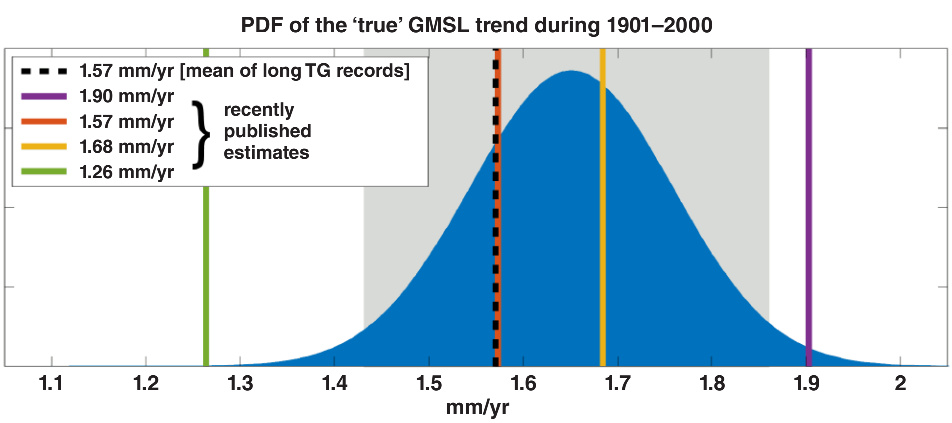


Figure 2. This graph shows the probability density function (PDF) for the true rate of twentieth century GMSL rise given how the tide gauges (TG) sample spatial structure in sea level change (bell curve). Gray shading represents 95% confidence intervals [±0.23 mm/yr (~0.009 in/yr)] about the central value of the distribution (1.66 mm/yr, (~0.07 in/yr)]. The black dashed line shows the sample mean of the observed trends from the tide gauge records; solid lines denote the linear rate of GMSL rise during 1901–2000 from four published twentieth century sea level reconstructions. (See Phil Thompson's presentation for specific references.) **Image credit:** Phil Thompson

Closing Plenary Highlights

In the closing session, participants heard summaries of each of the splinter sessions, and **François Boy** [CNES, Toulouse, France] reported on the SAR Altimetry Workshop and the Ninth Coastal Altimetry Workshop. This workshop focused on processing of SAR data and improving accuracy of altimeter data in the coastal zone. Details can be found at *http://www.coastalt.eu/restonworkshop15*

The meeting ended with an update on the status of reprocessing efforts for data from past and current altimeter missions. **Phil Callahan** [JPL] discussed reprocessing data for the TOPEX/Poseidon mission. Initial evaluation of retracked data has been completed and will be made available on the Physical Oceanography Distributed Active Archive Center (PO.DAAC) server soon (*https://podaac.jpl.nasa.gov*). Geophysical corrections still require updating, and applicability of some corrections remains uncertain. Work on reprocessing will continue into 2017, with additional help from and collaboration with CNES, notably for the updated geophysical corrections (GDR-E standards). **Nicolas Picot** [CNES] discussed the current GDR status for Jason-1, Jason-2, and SARAL/AltiKa.[7] The entire Jason-1 dataset is now available in GDR-E standards. Plans to reprocess Jason-2, Jason-3, and SARAL/AltiKa data to the new GDR-E standard are underway. For the calibration/validation phase, Jason-3 was based on GDR-D standard with orbit in GDR-E, fully in line with the Jason-2 standard.

After consideration by a dedicated "Extension of Life" working group (referred to as the "EoL subgroup") and discussion during the splinter sessions and the closing plenary session, the OSTST adopted a number of recommendations that appear in the *Summary of Recommendations from the OSTST* on page 34.

As has become customary, this OSTST meeting ended with a number of acknowledgments and kudos, several of which refer to the recommendations made by the OSTST. The team recognized CNES and NASA, for completing the Jason-1 reprocessing begun in 2013 as well as providing funding and support for this activity. They also recognized the Jason-3 project, for their hard work leading up to the successful launch of Jason-3 in early 2016. They also praised the Jason operational team for successfully executing the Jason-2 and -3 Formation Flight Phase (also called *tandem* phase), the move of Jason-2 to the interleaved orbit, and the smooth transition to drifting phase for SARAL/AltiKa. Finally, the OSTST congratulated ESA for successful launch of Sentinel-3A in February 2016 and recognized the high value of CryoSat Ocean Products for science.

The OSTST also acknowledged several key improvements to the Jason-CS/Sentinel-6 mission design, which should allow for improved performance over previous Jason missions. The altimeter and POD will be driven by the same ultrastable oscillator (USO) allowing easier error budgeting and capability to monitor the new USO against the existing GPS system. In addition, based on a previous OSTST recommendations, a high-frequency radiometer has been added, in order to improve coastal and inland water wet path delay corrections. Albeit experimental and nonredundant, the OSTST was particularly happy to see that their recommendation resulted in this concrete action.

Conclusion

Overall, the meeting was very successful, having fulfilled all its objectives. It provided a forum for an update on the status of Jason-2 and -3, and other relevant missions and programs, and detailed analyses of the observations by the splinter groups. The OSTST identified several objectives moving forward as identified in the sidebar on page 34.

The next OSTST Meeting will be held October 23-27, 2017, in Miami, FL. ■

[7] The SARAL/AltiKa project is a collaboration between CNES and the Indian Space Research Organization (ISRO). SARAL stands for Satellite with Argos and AltiKa; *saral* also means "simple" in Indian. Argos is a satellite-based system that collects, processes, and disseminates environmental data from fixed and mobile platforms, worldwide, that can locate the source of the data anywhere on Earth (*www.argos-system.org/?noca che=0.10773899871855974).* AltiKa is an innovative K_a-band altimeter that flies onboard SARAL.

U.S. Desert Songbirds at Risk in a Warming Climate

Samson Reiny, NASA's Earth Science News Team, samson.k.reiny@nasa.gov

EDITOR'S NOTE: This article is taken from *nasa.gov*. While it has been modified slightly to match the style used in *The Earth Observer*, the intent is to reprint it with its original form largely intact.

Projected increases in the frequency, intensity, and duration of heatwaves in the desert of the southwestern U.S. are putting songbirds at greater risk for death by dehydration and mass die-offs, according to a new study.[1]

Researchers used hourly temperature maps and other data produced by the North American Land Data Assimilation System (NLDAS)—a land-surface modeling effort maintained by NASA and other organizations—along with physiological data to investigate how rates of evaporative water loss in response to high temperatures varied among five bird species with differing body masses. Using these data, they were able to map the potential effects of current and future heat waves on lethal dehydration risk for songbirds in the Southwest and how rapidly dehydration can occur in each species—see **Figure 1**.

Researchers homed in on five songbird species commonly found in the desert southwest: lesser goldfinch, house finch, cactus wren, Abert's towhee, and the curve-billed thrasher.

Under projected conditions where temperatures increase by 4 °C (7 °F), which is in line with some scenarios for summer warming by the end of the century, heatwaves will occur more often, become hotter, and expand in geographic range to the point where all five species will be at greater risk for lethal dehydration.

A goldfinch sits on a branch. **Image credit:** Don Faulkner (CC BY-SA 2.0)

Birds are susceptible to heat stress in two ways, said co-author **Blair Wolf** [University of New Mexico—*Professor of Biology*]. With funding from the National Science Foundation, Wolf investigated heat tolerance

[1] To read the paper, visit *http://m.pnas.org/content/early/2017/02/07/1613625114*.

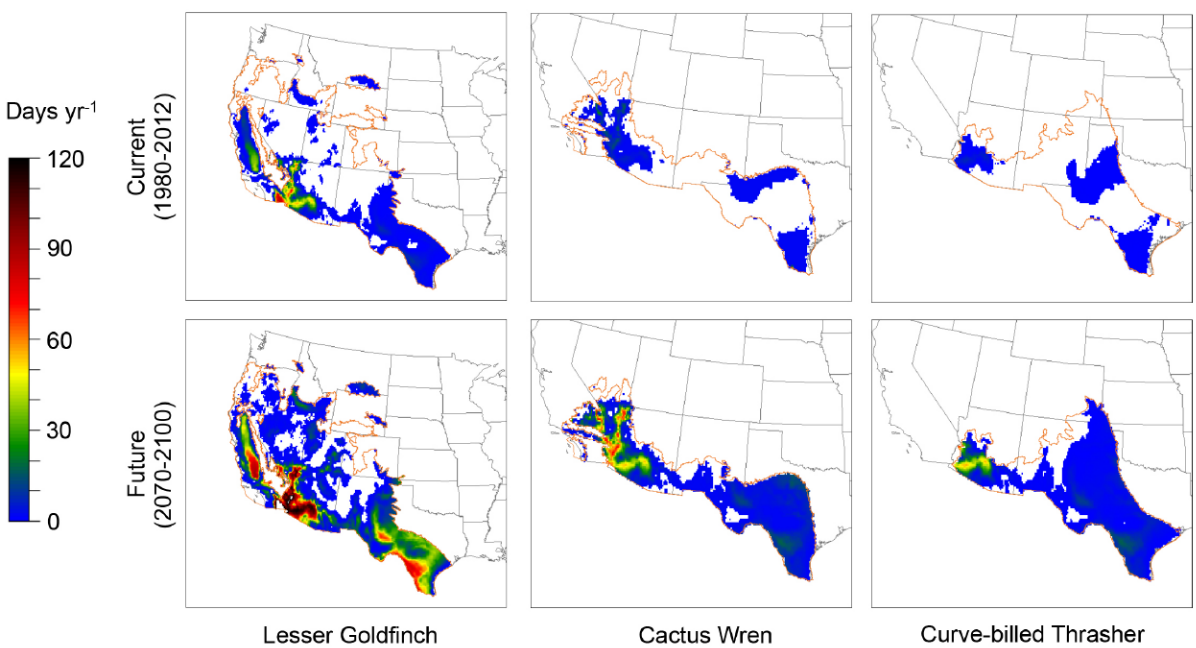


Figure 1. Days per year with modeled lethal dehydration risk for three songbird species under our current climate from 1980 to 2012 and under a 7 °F (~4 °C) future-warming scenario from 2070 to 2100. Species are arranged in order of increasing body mass. **Image credit:** NASA

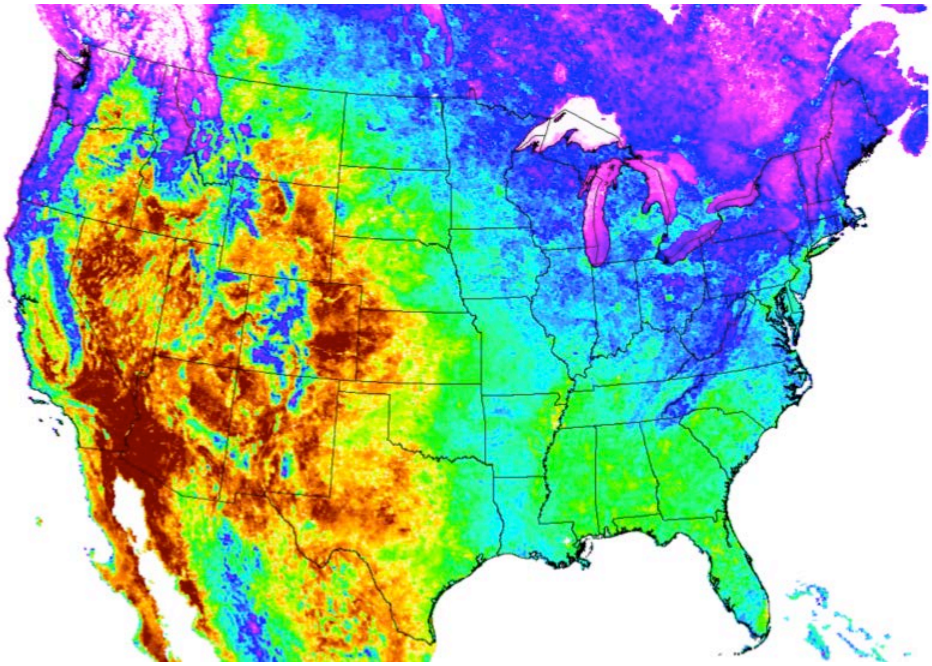


Figure 2. This map, created using data from NASA's Moderate Resolution Imaging Spectroradiometer, shows hotter than normal daytime land surface temperatures over much of the southwestern U.S., July 1-8, 2001. **Image credit:** NASA

for each of the five species in the study as well as for other bird species in Australia and South Africa. "When it's really hot, they simply can't evaporate enough water to stay cool, so they overheat and die of heat stroke," he said. "In other cases, the high rates of evaporative water loss needed to stay cool deplete their body water pools to lethal levels and birds die of dehydration. This is the stressor we focused on in this study."

What happens is at about 40 °C (104 °F), these songbirds start panting, which increases the rate of water loss very rapidly, explained co-author **Alexander Gerson** [University of Massachusetts, Amherst—*Assistant Professor of Biology*]. At the time of the study, he worked with Wolf as a postdoctoral researcher at the University of New Mexico. He added, "Most animals can only tolerate water losses that result in 15 or 20% loss of body mass before they die. So an animal experiencing peak temperatures during a hot summer day, with no access to water, isn't going to make it more than a few hours."

As expected, they found that the small species are particularly susceptible to lethal dehydration because they lose water at a proportionately higher rate. For example, at 50 °C (122 °F), the lesser goldfinch and the house finch lose 8 to 9% of their body mass to evaporative water loss per hour, whereas the larger Curve-billed thrasher only loses about 5% of its mass per hour. By the end of the century, the number of days in the southwest desert where lethal dehydration poses a high risk to the lesser goldfinch increases from 7 to 25 days per year—see **Figure 2** for example. For larger species, those days will also increase—but will remain rare.

Despite their physiological disadvantage, house finches and lesser goldfinches might actually fare comparatively better, the researchers noted, because they can survive in a number of ecosystems and they have a more expansive range. But desert specialists such as the curve-billed thrasher and Abert's towhee have more specific habitat needs and so have a more limited range, restricted in the U.S. mostly to the hot deserts of the Southwest. That means that a greater proportion of their population is at risk for lethal dehydration when severe enough heatwaves occur.

"When you get into a situation where the majority of the range is affected, that's where we start to become more alarmed at what we are seeing," said lead author **Tom Albright** [University of Nevada, Reno], noting that this increases the risk of lethal dehydration affecting a large proportion of the population.

According to the researchers, given this warming scenario, climate *refugia*—microclimates such as mountaintops, trees, and washes with shade that allow songbird body temperatures to cool to safe levels—might prove very important in management plans for certain vulnerable species. "Using this type of data, managers identifying the best refugia can have a better idea of the temperature profile that will be suitable for these birds," Gerson said.

This research is part of a global effort among researchers from the U.S., South Africa, and Australia to more thoroughly understand the physiological responses of birds to increasing temperatures, with the goal of broadening our understanding of how rising temperatures will affect individuals, populations, and community structure. ■

NASA Says Goodbye to a Pathfinder Earth Satellite After 17 Years

Kasha Patel, NASA's Goddard Space Flight Center, kasha.g.patel@nasa.gov

EDITOR'S NOTE: This article is taken from *nasa.gov*. While it has been modified slightly to match the style used in *The Earth Observer*, the intent is to reprint it with its original form largely intact.

The first to map active lava flows from space.

The first to measure a facility's methane leak from space.

The first to track regrowth in a partially logged Amazon forest from space.

After 17 years in orbit, one of NASA's pathfinder Earth satellites for testing new satellite technologies and concepts came to an end on March 30, 2017. The Earth Observing-1 (EO-1) satellite (shown in **Figure 1**) was powered off on that date but will not enter Earth's atmosphere until 2056.

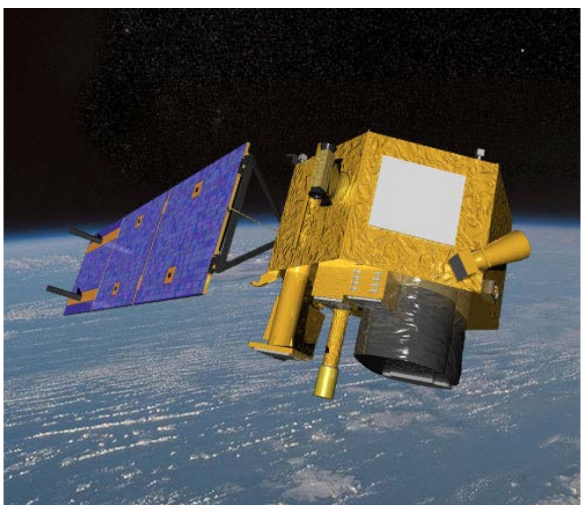


Figure 1. Artist's rendering of the Earth Observing-1 spacecraft flying over Earth. **Image credit**: NASA's Science Visualization Studio

Launched on November 21, 2000, EO-1 was designed as a technology validation mission focused on testing cutting-edge satellite and instrument technologies that could be incorporated into future missions. Commissioned as part of NASA's New Millennium Program, the satellite was part of a series of missions that were developed at a cheaper price tag to test new technologies and concepts that had never been flown before.

"EO-1 has changed the way spectral Earth measurements are being made and used by the science community," said **Betsy Middleton** [NASA's Goddard Space Flight Center—*EO-1 Project Scientist*].

EO-1 was launched with 13 new technologies—including 3 new instruments. EO-1's most important technology goal was to validate the Advanced Land Imager (ALI) for future Earth-observing satellites. ALI provided a variety of Earth data including observations of forest cover, crops, coastal waters, and aerosols. ALI's instrument design and onboard technology directly shaped the design of the Operational Land Imager (OLI) on Landsat 8, currently in orbit.

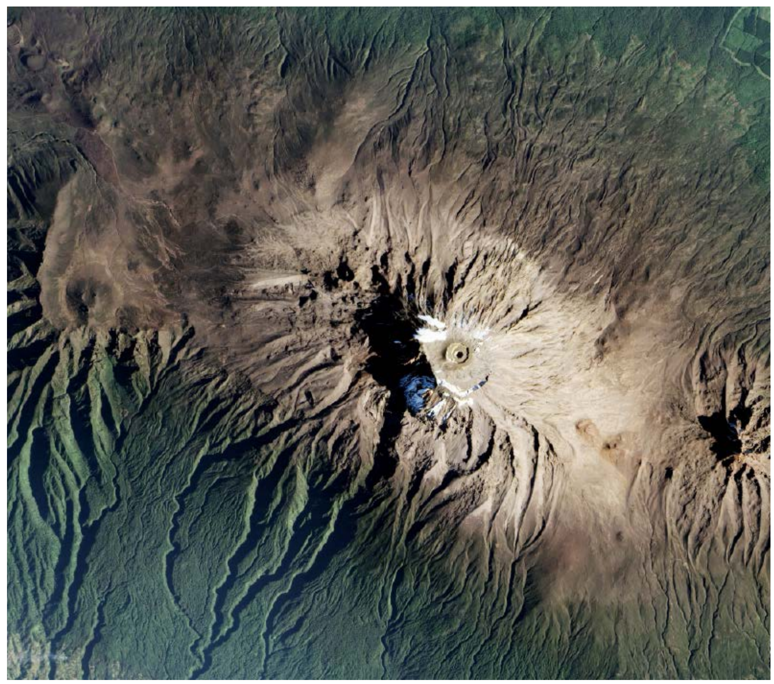
EO-1's other key instrument is a hyperspectral instrument called Hyperion that allowed scientists to see chemical constituents of Earth's surface in fine detail with hundreds of wavelengths. These data allow scientists to identify specific minerals, track vegetation type and vigor of forests, and monitor volcanic activity. The knowledge acquired and technology developed from Hyperion is being incorporated into a NASA concept for a potential future hyperspectral satellite, the Hyperspectral Infrared Imager (HyspIRI), that will study the world's ecosystems, such as identifying different types of plants and assessing wildfires and droughts.

With both of these instruments, the EO-1 team was able to acquire images with high spatial resolution of events and natural disasters around the world for anyone who requested it. The EO-1 team could point the instruments at any specific location and gather images every two to five days of a particular spot, which was very useful for scientists as well as disaster relief managers trying to stay informed of rapidly changing events. (Landsat typically looks at the same area once every 16 days.) EO-1 captured scenes such as the ash after the World Trade Center attacks, the flooding in New Orleans after Hurricane Katrina, volcanic eruptions (example shown in **Figure 2**), and a large methane leak in southern California.

EO-1 also served as a valuable pathfinder for a variety of space technologies. Technologists installed and tested autonomy software on EO-1 that allowed the satellite to make its own decisions based on the content of the data it collected. For instance, if a scientist instructed EO-1 to take a picture of an area where a volcano was currently erupting, the software could decide to automatically take a follow-up image the next time it passed over the location.

The mission also validated software that allowed "formation flying" that kept EO-1 orbiting Earth exactly one minute behind the Landsat 7 satellite, already in orbit. The original purpose was to validate the new ALI technologies for use in Landsat 8, which was accomplished.

Figure 2. This image, taken by EO-1's Advanced Land Imager on February 10, 2012, shows an underwater volcanic eruption off El Hierro Island in the Atlantic Ocean. **Image credit**: NASA's Earth Observatory



This image, taken by EO-1's Advanced Land Imager (ALI) on January 20, 2017, shows snowcap of the volcanic Mount Kilimanjaro. **Image credit:** NASA's Earth Observatory

EO-1 was originally only supposed to last one year,[1] but after that initial mission, the satellite had no major issues or breakdowns. On a shoestring budget contributed by NASA, the U.S. Geological Survey, the National Oceanic and Atmospheric Administration, National Reconnaissance Office, and Naval Research Laboratory, the satellite continued to operate for 16 more years, resulting in more than 1500 papers published on EO-1 research.

[1] To learn more about the accomplishments of EO-1, see "EO-1: 15 Years After the Start of Its 'One-Year' Mission" in the January–February 2016 issue of *The Earth Observer* [**Volume 28**, **Issue 1**, pp. 4-14]. Also see *https://eo1.gsfc.nasa.gov* or *https://eospso.nasa.gov/missions/earth-observing-1*.

On March 30, 2017, the satellite was decommissioned, drained of its energy, and became inert. Without enough fuel to keep EO-1 in its current orbit, the mission team shut down the satellite and will wait for it to return to Earth. When EO-1 does reenter Earth's atmosphere in about 39 years, it is estimated that all the components will burn up in the atmosphere.

"We'll probably just see EO-1 as a streak in the sky as it disintegrates," said Middleton. ■

NASA Data Show California's San Joaquin Valley Still Sinking

Alan Buis, NASA/Jet Propulsion Laboratory, alan.buis@jpl.nasa.gov
Ted Thomas, California Department of Water Resources, Ted.Thomas@water.ca.gov

EDITOR'S NOTE: This article is taken from *nasa.gov*. While it has been modified slightly to match the style used in *The Earth Observer*, the intent is to reprint it with its original form largely intact.

Since the 1920s, excessive pumping of groundwater at thousands of wells in California's San Joaquin Valley has caused land in sections of the valley to subside, or sink, by as much as 28 ft (8.5 m). This subsidence is exacerbated during droughts, when farmers rely heavily on groundwater to sustain one of the most productive agricultural regions in the nation.

Long-term subsidence is a serious and challenging concern for California's water managers, putting state and federal aqueducts, levees, bridges, and roads at risk of damage. Already, land subsidence has damaged thousands of public and private groundwater wells throughout the San Joaquin Valley. Furthermore, the subsidence can permanently reduce the storage capacity of underground aquifers, threatening future water supplies. It's also expensive. While there is no comprehensive estimate of damage costs associated with subsidence, state and federal water agencies have spent an estimated $100 million on subsidence-related repairs since the 1960s.

To determine the extent to which additional groundwater pumping associated with California's current historic drought, which began in 2012, has affected land subsidence in the Central Valley, California's Department of Water Resources (DWR) commissioned NASA/Jet Propulsion Laboratory (JPL) to use its expertise in collecting and analyzing airborne and satellite radar data. An initial report of the JPL findings[1] (August 2015) analyzed radar data from several different sensors between 2006 and early 2015. Due to the continuing drought, DWR subsequently commissioned JPL to collect and analyze new radar images from 2015 and 2016 to update DWR on the land subsidence.

How Much Sinking?

Several trouble spots identified in the first report continue to subside at rates as high as 2 ft (0.6 m) a year—see **Figure**. Significant subsidence was measured in two

[1] To read the full report, visit *http://water.ca.gov/groundwater/docs/NASA_REPORT.pdf.*

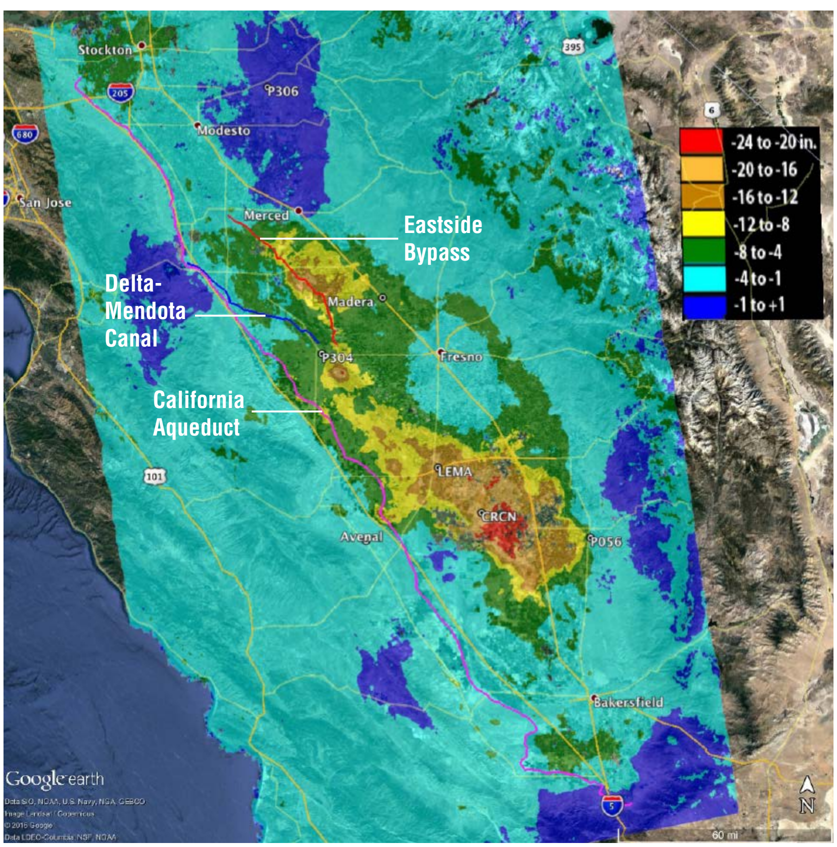


Figure. Total subsidence in California's San Joaquin Valley between May 7, 2015 and September 10, 2016, as measured by the advanced C-band synthetic aperture radar on the European Space Agency's Sentinel-1A satellite. (The data are processed at JPL). Two large subsidence bowls are evident, centered on Corcoran and southeast of El Nido, with a small, new feature between them, near Tranquility. **Image credit:** European Space Agency/NASA-JPL/Caltech/Google Earth subsidence bowls located near the towns of Chowchilla, south of Merced; and Corcoran, north of Bakersfield. These bowls cover hundreds of square miles and continued to grow wider and deeper between May 2015 and September 2016. Maximum subsidence during this time period was almost 2 ft (0.6 m) in the Corcoran area and about 16 in (41 cm) near Chowchilla. Subsidence also intensified near Tranquility in Fresno County during the past year, where the land surface has settled up to 20 in (51 cm) in an area that extends 7 mi (11 km). Subsidence in these areas affects aqueducts and flood control structures.

Small amounts of land subsidence were also identified in the Sacramento Valley near Davis and Arbuckle. A small area observed for the first time in Sierra Valley, north of Lake Tahoe, shows about 6 in (15 cm) of subsidence.

JPL scientists plotted the history of subsidence of several sites in the mapped areas and found that for some areas in the San Joaquin Valley, subsidence slowed during the winter of 2015-16 when rainfall matched crop water needs. "While we can see the effect that rain has on subsidence, we know that we've run a groundwater deficit for some time, so it'll take a long time to refill those reservoirs," said report co-author **Tom Farr** [JPL].

The report update also examined California's South Central coast, including Ventura, Oxnard, Santa Barbara, and north to the San Joaquin Valley, as well as the Santa Clara Valley. It found no major areas of subsidence in these regions, though a known area of subsidence in the Cuyama Valley was observed to have continued land subsidence.

Report co-author **Cathleen Jones** [JPL] said being able to pinpoint where subsidence is happening helps water resource managers determine why it is happening. "If you see a subsidence bowl, then something is going on at the center of the bowl that is causing the land to sink—for example, high levels of groundwater pumping," Jones said. "We can locate problem spots so the state can focus on those areas, saving money and resources. We find the needle in the haystack, so to speak."

How the Study Was Done

To obtain the subsidence measurements, JPL scientists compared multiple satellite and airborne interferometric synthetic aperture radar (InSAR) images of Earth's surface acquired as early as 2006 to produce maps showing how subsidence varies over space and time. InSAR is routinely used to produce maps of surface deformation with approximately half-inch-level (centimeter-level) accuracy.

The subsidence maps in the new report were created by analyzing satellite data from the European Space Agency's Sentinel-1A satellite from March 2015 to September 2016, and from NASA's airborne Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) from March 2015 to June 2016. The new data complement the data used in the previous report from Japan's Phased Array type L-band Synthetic Aperture Radar (PALSAR, 2006 to 2010), Canada's Radarsat-2 (May 2014 to January 2015) and UAVSAR (July 2013 to March 2015).

How Subsidence Affects Key California Water Supply Routes

The high-resolution airborne UAVSAR radar mapping was focused on the California Aqueduct—the main artery of the State Water Project, which supplies 25 million Californians and nearly a million acres of farmland. The aqueduct is a system of canals, pipelines, and tunnels that carries water 444 mi (715 km) from the Sierra Nevada and Northern/Central California valleys to Southern California.

The JPL report shows that localized subsidence directly impacting the aqueduct is ongoing, with maximum subsidence of the structure reaching 25 in (64 cm) near Avenal in Kings County. As a result of subsidence in this area since the initial aqueduct construction, the aqueduct there can now carry a reduced flow of only 6,640 ft^3 (188 m^3) per second—20% less than its design capacity of 8,334 ft^3 per second (236 m^3 per second). Water project operators must reduce flows in the sections that have sunk to avoid overtopping the concrete banks of the aqueduct.

DWR, which operates the State Water Project, is analyzing whether the subsidence-created dip in the California Aqueduct will affect deliveries to water districts in Kern County and Southern California. If the State Water Project allocation is 85% or greater, delivery may be impaired this year due to cumulative subsidence impacts in the Avenal-Kettleman City area.

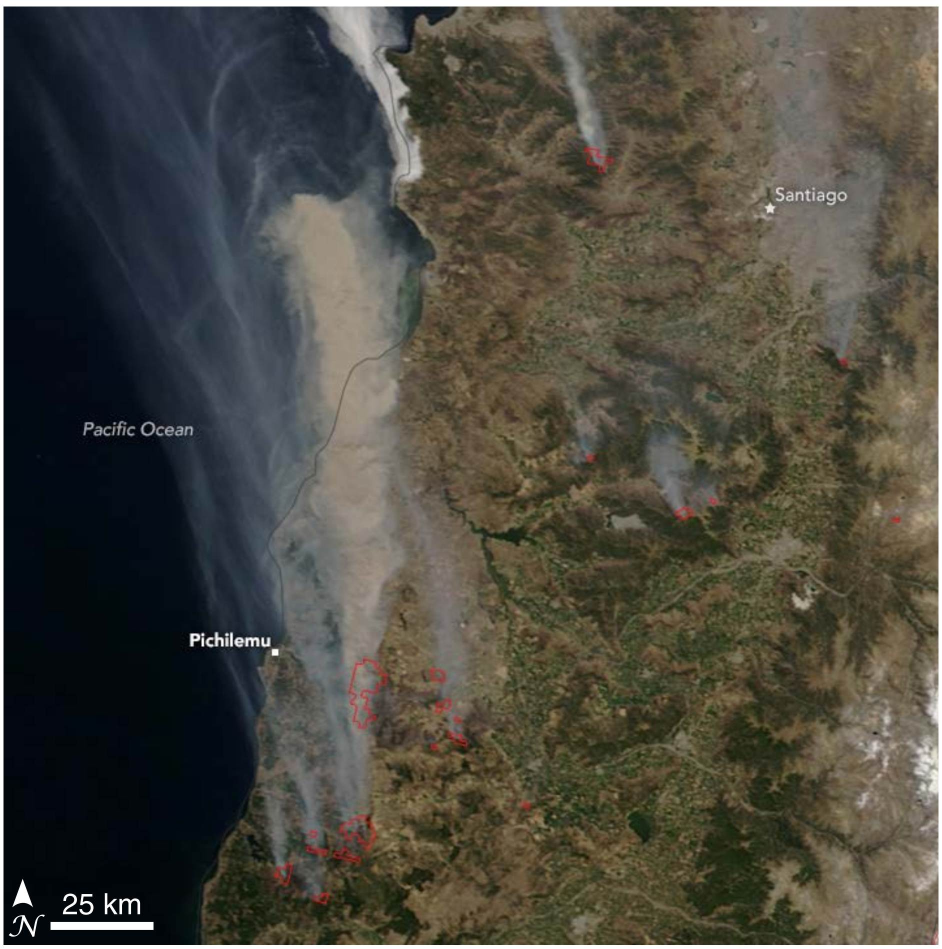
The new NASA analysis also found subsidence of up to 22 in (56 cm) along the Delta-Mendota Canal, a major artery of the Central Valley Project (CVP), operated by the U.S. Bureau of Reclamation. The CVP supplies water to approximately three million acres of farmland and more than two million Californians.

Also of concern is the Eastside Bypass, a system designed to carry flood flow off the San Joaquin River in Fresno County. The bypass runs through an area of subsidence where the land surface has lowered between 16 and 20 in (41 and 51 cm) since May 2015, on top of several feet of subsidence measured between 2008 and 2012. DWR is working with local water districts to analyze whether surface deformation may interfere with flood-fighting efforts, particularly as a heavy Sierra snowpack melts this spring. A 5-mi (8-km) reach of the Eastside Bypass was raised in 2000 because of subsidence, and DWR estimates it may cost in the range of $250 million to acquire flowage easements and levee improvements to restore the design capacity of the subsided area.

"The rates of San Joaquin Valley subsidence documented since 2014 by NASA are troubling and unsustainable," said **William Croyle** [DWR—*Director*]. "Subsidence has long plagued certain regions of California. But the current rates jeopardize infrastructure serving millions of people. Groundwater pumping now puts at risk the very system that brings water to the San Joaquin Valley. The situation is untenable."

The upcoming NASA and Indian Space Research Organisation (ISRO) Synthetic Aperture Radar (NISAR) mission, will systematically collect data over California and the world and will be ideal for measuring and tracking changes to the land subsidence associated with groundwater pumping, as well as uplift associated with natural and assisted groundwater recharge.

To read the new report, visit: *http://www.water.ca.gov/waterconditions/docs/2017/JPL%20subsidence%20report%20final%20for%20public%20dec%202016.pdf.* ■



Smoke from dozens of forest fires billowed over central Chile in January 2017. A heat wave, coupled with strong winds, spread the flames on January 20, prompting President Michelle Bachelet to declare a state of emergency in some areas.

On January 20, 2017, the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Terra satellite acquired an image of smoke billowing from a cluster of fires near the coastal city of Pichilemu. Red outlines indicate areas with heat signatures indicative of active burning. Smoke plumes stretch northward and over the Pacific Ocean.

There were 108 active forest fires registered in Chile on January 23, 2017. According to an update by the National Forest Corporation (CONAF), 62 had been controlled and three had been extinguished. The remaining 43 fires spanned an area of roughly 104,800 hectares (more than 400 square miles), according to CONAF.

Chile recorded roughly 5200 forest fires per season in the decade between 1990 and 2000, according to a report by the United Nations Food and Agriculture Organization. The country has a Mediterranean climate and a long dry season—conditions that facilitate fires. Chile registered more than 6700 fires during the 2015–16 fire season. **Image credit**: NASA, Jeff Schmaltz, LANCE/EOSDIS Rapid Response. **Caption credit:** Pola Lem

NASA Earth Science in the News

Samson Reiny, NASA's Earth Science News Team, samson.k.reiny@nasa.gov

Study: Vast Majority of Wildfires Started by Humans, March 7, *cnn.com*. The devastating wildfires that tore through Gatlinburg, TN, in December 2016, were extraordinary—they left 14 people dead and injured another 175. But they were also typical wildfires in one way: Authorities say they were caused by humans. According to a NASA-funded study published in the *Proceedings of the National Academy of Sciences* in February, 84% of wildfires in the U.S. are caused by people. The study, by professor **Jennifer K. Balch** [University of Colorado, Boulder] and other colleagues, examined government agency wildfire records from 1992-2012. It is one of the largest projects of its kind. The analysis found that human-started wildfires have tripled the length of the wildfire season and accounted for a total of 44% of all acreage burned. Lightning-sparked wildfires are mostly concentrated in summer, but human activity has expanded the fire season to include spring and fall.

***NASA Perfects Sea Ice Forecasting Technique**, March 6, *cosmosmagazine.com*. NASA has developed a new forecasting model that allows researchers to make better estimates of the rate of loss of Arctic sea ice. Each year during Northern Hemisphere spring months scientists are faced with the tricky task of estimating exactly how much ice will disappear from its maximum wintertime extent. Such information is vital for the Navy, shipping companies, and native people who depend on sea ice for hunting. NASA satellites have been measuring sea ice in the Arctic since 1979, so the simplest approach to making an estimate is to assume a continuation of the long-term trend but that risks missing outlier years with a higher or lower ice extent. So researchers have developed a new model that analyzes the physical characteristics of the sea ice cover as the melt season develops, which enables them to compare it to long-term trends. "What we have shown is that we can use information collected in the spring and onwards to determine if we should see more or less ice come the end of summer than expected from the long-term decline," said **Alek Petty** [NASA's Goddard Space Flight Center (GSFC)—*Research Associate*], lead author of the new paper, which was published in the journal *Earth's Future*.

How Much Water is Locked Up in World's Mountain Snow? NASA Wants to Know, February 28, *techtimes.com*. Obstacles to determine how much water is locked up in the world's mountain snow have yet to be conquered. No single instrument, even space-based, had ever come close to hurdling them. Against this backdrop, NASA's SnowEx has joined the fray with a goal—to find the best snow-measuring techniques. "This is the most comprehensive campaign we have ever done on snow," declared **Edward Kim** [GSFC—*SnowEx Project Scientist*]. Approximately 70% of the world's surface is covered by water, of which only 2.5% of this is fresh water. Of the available fresh water, more than two-thirds is locked in glaciers. In addition, about 20% of the Earth's land surface is covered by snow, which also has water locked in it. This has far-reaching consequences on a society where more than a billion people depend largely on snow for their fresh water, Kim said. The water locked in the world's mountain snow has other consequences for people, such as devastating floods, drought, and instability when its supply is scarce.

Researcher's 1979 Arctic Model Predicted Current Sea Ice Demise, Holds Lesson for Future, February 20, *insideclimatenews.org*. **Claire Parkinson** [GSFC—*Senior Climate Scientist*] first began studying global warming's impact on Arctic sea ice in 1978, when she was a promising new researcher at the National Center for Atmospheric Research. Back then, what she and a colleague found was not only groundbreaking, it quite accurately predicted what is happening now in the Arctic, as sea ice levels break record low after record low. Parkinson's study, which was published in 1979, found that a doubling of atmospheric carbon dioxide from preindustrial levels would cause the Arctic to become ice-free in late summer months, probably by the middle of the twenty-first century. (The Arctic hasn't been ice-free in more than 100,000 years.) Although carbon dioxide levels have not yet doubled, the ice is rapidly disappearing. This record melt confirms the outlook from Parkinson's 1979 model. "It was one of these landmark papers," said **Mark Serreze** [National Snow and Ice Data Center—*Director*].

NASA Satellite Photos Show Effects of California Rain, February 22, *cnn.com*. Photos from NASA's Earth Observatory website show the aftereffects of massive amounts of rain on California's hydrologic system—see **Figure 1**. The National Oceanic and Atmospheric Administration says strong atmospheric rivers can transport 7.5-to-15 times the average water flow at the mouth of the Mississippi River. These flowing columns of condensed water vapor produce "significant levels of rain and snow," and can account for 30–50% of the Pacific Coast's rain and snow. Atmospheric rivers are usually 250–375 mi (402–604 km) wide. Satellite photos published by NASA show how rain caused by California's most recent atmospheric river is carrying sediment through waterways and dumping it into the Pacific Ocean.

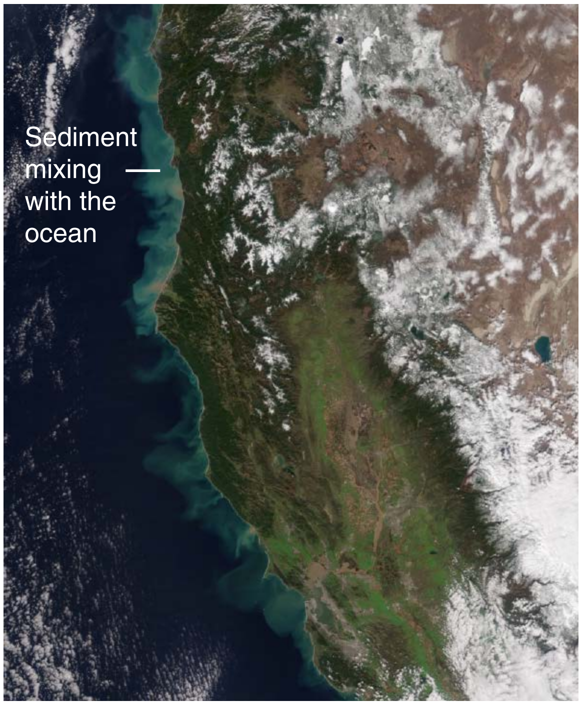


Figure 1. On February 11, 2017, the Visible Infrared Imaging Radiometer Suite (VIIRS) on the Suomi National Polar-orbiting Partnership satellite acquired this remarkable view of the coast of California showing rivers and streams spewing sediment into the Pacific Ocean after recent atmospheric-river-induced heavy rains. **Image credit:** NASA's Earth Observatory

NASA To Launch Sequel to Successful Lightning Study Mission, February 17, *spacedaily.com*. NASA is set to reboot a successful study of Earth's lightning from space—this time from the unique vantage point of the International Space Station (ISS). A team of Earth scientists at NASA's Marshall Space Flight Center (MSFC) in Huntsville, AL, and the University of Alabama in Huntsville have high hopes for a follow-up mission for the agency's Lightning Imaging Sensor (LIS)[1] first launched into space in 1997 onboard the Tropical Rainfall Measuring Mission (TRMM). Now, an identical LIS—built as a back-up—is headed to the space station for a two-year mission to probe the mysteries of lightning and its connections to other atmospheric phenomena. LIS is a sophisticated lightning research instrument designed to measure the amount, rate, and optical characteristics of lightning over Earth. Mounted externally on the station in an Earth-viewing position, the spare LIS will build on the foundation of space-based lightning observations begun by its predecessor. "The LIS used in this follow-on mission is an exact duplicate of the sensor used on TRMM," said **Richard Blakeslee** [MSFC—*LIS Project Scientist*]. "But it will sample lightning over a wider geographical area."

[1] **UPDATE**: LIS (and SAGE-III) successfully launched on February 19, 2017, and has been installed on the ISS. To learn more about the mission, read "LIS on ISS: Expanded Global Coverage and Enhanced Applications" in the May–June 2016 issue of *The Earth Observer* [**Volume 28**, **Issue 3**, pp. 4-14].

January 2017 Emerges as Third Hottest In 137 Years: NASA, February 17, *techtimes.com*. While January 2017 did not get a further temperature boost from the El Niño that affected the same period in the previous year, it doesn't mean it's not record warm. In fact, it has emerged as the third hottest January in 137 years of modern record-keeping. This finding was released by scientists at NASA's Goddard Institute for Space Studies, based on a monthly global temperature analysis. In January 2017, the global temperature was 0.20 °C (0.36 °F) cooler than it was in January 2016, the warmest recorded January, but it was 0.92 °C (1.66 °F) warmer than the mean temperature of January from 1951 to 1980. On the upside, January 2017 appeared to be the first time in a while that global temperatures strayed from a steady upward trend, but it placed third among modern January records, where 2016 was the hottest at 1.12 °C (2.01 °F) warmer than the mean temperature. Not far behind it in second place is 2007 at 0.96 °C (1.73 °F) warmer than the base period. The monthly GISS analysis is based on data from around 6300 meteorological centers worldwide, ship- and buoy-based instruments that measure sea surface temperature, and research posts in the Antarctic region. Observations began in 1880, as the ones before that did not cover enough of Earth.

OMG, It's the Greenland Ice Sheet, February 15, *cosmosmagazine.com*. NASA's Oceans Melting Greenland (OMG) is a five-year campaign to study the glaciers and ocean along Greenland's 43,000-km (~26,718-mi) coastline. Its goal is to find out where and how fast seawater is melting the glacial ice. Most of the coastline and seafloor around the ice sheet had never been surveyed, so the 2016 flights significantly expanded scientists' knowledge of Greenland. The water circulating close around the Greenland ice sheet is like a cold river floating atop a warm, salty ocean. The top 200 m (~656 ft) of colder water is relatively fresh and comes from the Arctic. Below that is saltwater that comes from the south and is 3 to 4 °C (5 to 7 °F) warmer than the fresher water above. The layers don't mix much because freshwater is less dense than saltwater, so it stays afloat. If a glacier reaches the ocean where the seafloor is shallow, the ice interacts with frigid freshwater and melts slowly. Conversely, if the seafloor in front of a glacier is deep, the ice spills into the warm subsurface layer of saltwater and may melt relatively rapidly. Satellite remote sensing can't see below the surface to discern the depth of the seafloor or study the layers of water but observations obtained by shipboard and airborne instruments during OMG can.

[*] See News story in this issue to learn more.

*Interested in getting your research out to the general public, educators, and the scientific community? Please contact **Samson Reiny** on NASA's Earth Science News Team at **samson.k.reiny@nasa.gov** and let him know of upcoming journal articles, new satellite images, or conference presentations that you think would be of interest to the readership of **The Earth Observer**.*

NASA Science Mission Directorate – Science Education and Public Outreach Update

These items were obtained from *http://www.nasa.gov/audience/foreducators*. While in some cases the information has been modified to match the style of *The Earth Observer,* the intent is to reprint it with its original form largely intact.

Celebrate Women's History Month: Download New NASA Women of Color Lithograph

Through their accomplishments and dedication to their jobs, women at NASA make manifest the essence of Women's History Month. They serve as role models to young women—and others!—in their pursuits of careers in science, technology, engineering, and mathematics.

The new *Women of Color: Pioneers and Innovators* lithograph features administrators, astronauts, pilots, and mathematicians who have been or are currently pioneers and innovators in the fields of aeronautics and astronautics. To download this lithograph, visit *https://www.nasa.gov/audience/foreducators/topnav/materials/listbytype/Women_of_Color_Lithograph.html*.

Are you looking for more insight into the innovative work being done by women across NASA? Visit the NASA *Women of STEM* website to read career profiles, watch videos, and more! Check it out at *http://www.nasa.gov/education/womenstem*.

Educator Workshop: The Little Blue Dot—Earth Science for Middle School Teachers

Workshop Date—June 12-15, 2017

Are you a highly motivated middle school teacher who wants to increase your knowledge of Earth science? Sign up today to attend a workshop, *The Little Blue Dot—Earth Science for Middle School Teachers*. Sponsored by the Texas Space Grant Consortium, this workshop will take place June 12-15, 2017, at the University of Texas in Austin.

Workshop attendees will learn about hands-on activities designed to support Earth-science educational standards in grades 6-8. NASA scientists and engineers will share their expertise and the latest findings in Earth-science research. Participants will earn 24 hours of professional development credit in Earth science.

For more information, visit *http://www.tsgc.utexas.edu/earth-science-workshop*.

Get Ready for the 2017 Solar Eclipse With NASA Resources

On August 21, 2017, the United States will experience a solar eclipse! This celestial event will provide a golden opportunity to engage and educate diverse audiences, and NASA has the resources to help.

Along a path 60 to 70 miles wide stretching from Oregon to South Carolina, observers will be able to see a total solar eclipse. Others across North America will see a partial eclipse. For an interactive map with timing information along the path of the eclipse, visit *http://eclipse.gsfc.nasa.gov/SEgoogle/SEgoogle2001/SE2017Aug21Tgoogle.html*.

Visit the following websites to find additional information and resources, including:

- tips for safely viewing the solar eclipse;
- recorded interviews with NASA scientists, mission specialists, and eclipse-path communities;
- topical online eclipse videos—featuring a variety of STEM and cultural topics;
- social media community development and networking;
- mobile educational eclipse applications;
- public challenges and engagement activities;
- two-dimensional and three-dimensional printing exercises for K-12 students;
- citizen science campaigns in partnership with NASA mission observations;
- adjunct activities and educational resources; and
- live streaming of observations and programming.

Total Eclipse 2017—Through the Eyes of NASA
http://eclipse2017.nasa.gov

Eclipses and Transits
http://www.nasa.gov/eclipse

"The Solar Eclipse 2017 PREVIEW Show" (NASA EDGE)
https://youtu.be/6DDICymjhg0. ■

EOS Science Calendar

May 16–18, 2017
CERES Science Team Meeting,
NASA's Langley Reseach Center, VA.
https://ceres.larc.nasa.gov/science-team-meetings2.php

May 17–19, 2017
CLARREO Science Definition Team Meeting,
Boulder, CO.

September 12–14, 2017
OMI Science Team Meeting,
Greenbelt, MD.

October 3–4, 2017
DSCOVR EPIC/NISTAR Science Team Meeting,
Greenbelt, MD.

October 10–12, 2017
GRACE Science Team Meeting,
Austin, TX.

October 23–27, 2017
Ocean Surface Topography Science Team Meeting,
Miami, FL.

March 19–23, 2018
2018 Sun-Climate Symposium,
Lake Arrowhead, CA.
http://lasp.colorado.edu/home/sorce/news-events/meetings/2018-scs

Global Change Calendar

April 23–28, 2017
European Geosciences Union, Vienna, Austria.
http://www.egu2017.eu

May 20–25, 2016
JpGU-AGU Joint Meeting, Chiba, Japan.
http://www.jpgu.org/meeting_e2017

July 23–28, 2017
IEEE International Geoscience and Remote Sensing Symposium, Fort Worth, TX.
http://www.igarss2017.org

August 6–11, 2017
Annual Meeting Asia Oceania Geosciences Society, Singapore.
http://www.asiaoceania.org/aogs2017/public.asp?page=home.htm

December 11–15, 2017
AGU Fall Meeting, New Orleans, LA.
http://fallmeeting.agu.org/2016/2017-fall-meeting-new-orleans

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Articles, contributions to the meeting calendar, and suggestions are welcomed. Contributions to the calendars should contain location, person to contact, telephone number, and e-mail address. Newsletter content is due on the weekday closest to the 1st of the month preceding the publication—e.g., December 1 for the January–February issue; February 1 for March–April, and so on.

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The Earth Observer Staff

Executive Editor:	Alan B. Ward (alan.b.ward@nasa.gov)
Assistant/Technical Editors:	Heather H. Hanson (heather.h.hanson@nasa.gov) Mitchell K. Hobish (mkh@sciential.com)
Technical Editor:	Ernest Hilsenrath (hilsenrath@umbc.edu)
Design, Production:	Deborah McLean (deborah.f.mclean@nasa.gov)

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