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Editor's Corner

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On November 19, 2016, NOAA's GOES-R weather satellite (now known as GOES-16) was launched from the Cape Canaveral Air Force Station in Florida on a United Launch Alliance (ULA) Atlas V rocket. This is the first in a series of U.S. satellites that will extend the availability of operational geosynchronous observations into the 2036 timeframe.[1] The new GOES-R series carries the Advanced Baseline Imager (ABI), which offers greatly improved spectral, spatial, and temporal resolution over previous sensors, and the Geostationary Lightning Mapper (GLM), which is the first of its kind in geosynchronous operation. Along with its space weather instruments, the new series provides advanced capabilities for forecasts and warnings, as well as unique observations for Earth science and application studies.

Beginning on December 8, GOES-16 will undergo an approximately year-long check-out phase at a longitude of 89.5° W. NASA and NOAA will work closely together on performance validation. An ABI Level-1 radiometric validation airborne campaign is planned for March 2017 using the NASA high-altitude ER-2 aircraft flying out of Palmdale, CA. This will be followed by a campaign emphasizing ABI Level-2 and GLM Level-1/Level-2 products with the ER-2 flying out of Warner Robbins, GA. The ER-2 instrument complement includes a variety of NASA (GSFC, MSFC, and JPL) and university sensors in close coordination with the NOAA NESDIS Calibration and Algorithm Working Group science teams. This effort continues the long history of close

[1] Launches of GOES-S, -T, and -U are tentatively planned for 2018, 2019, and 2024 respectively.

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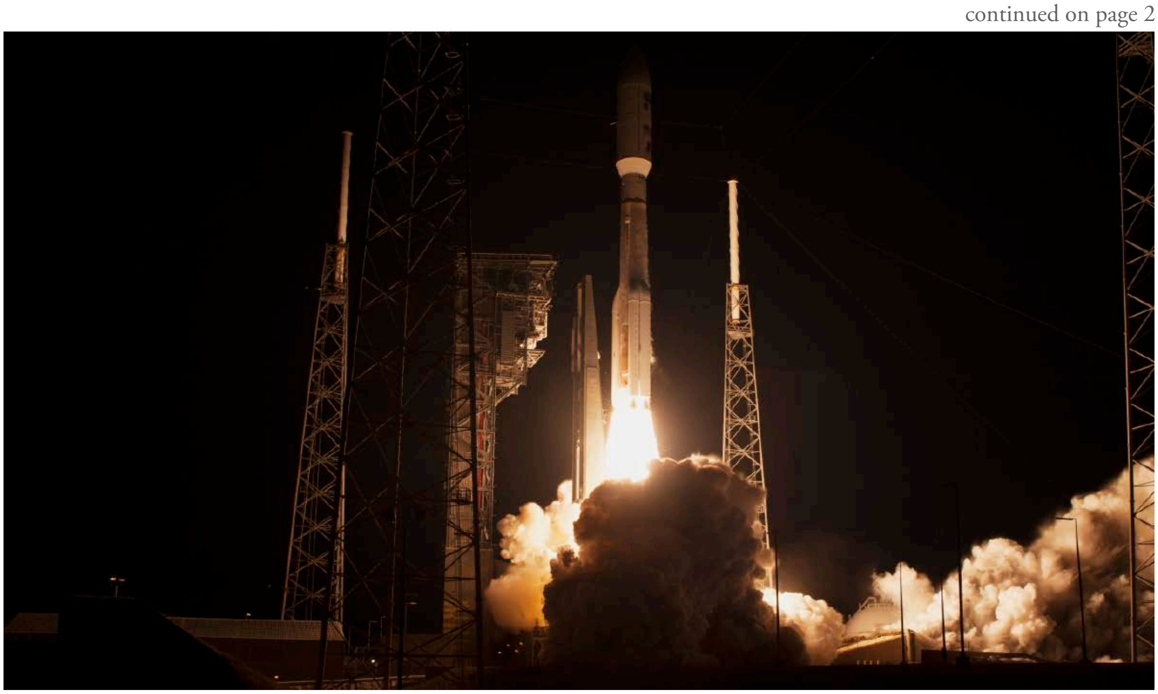

Shown here is a photo of the launch of a United Launch Alliance (ULA) Atlas V rocket from Cape Canaveral Air Force Station in Florida on November 19, 2016 carrying NOAA's GOES-R weather satellite (now known as GOES-16) into orbit. GOES-16 is the first in a series of three planned launches that will extend the availability of U.S. operational geosynchronous observations into the 2036 timeframe. This effort continues the long history of close collaborations between NASA and NOAA on the development, acquisition and launch of U.S. geosynchronous and polar weather satellites. **Photo credit:** NASA/Tony Gray and Tim Terry

www.nasa.gov

In This Issue

To view a list of undefined acronyms used in the editorial and table of contents see page 55.

collaborations between NASA and NOAA on the development, acquisition, and launch of U.S. geosynchronous and polar weather satellites. Congratulations to the entire GOES-R team on the launch and best wishes for a successful GOES-16 mission. Further detail can be found at *http://www.goes-r.gov*.

As this issue goes to print, final preparations were underway for the launch of the Cyclone Global Navigation Satellite System (CYGNSS) mission, which is scheduled to launch on December 12, 2016 also from Cape Canaveral. CYGNSS is the first NASA Earth Venture Mission (EVM[2]) to launch. It will deploy a fleet of eight microsatellites from a single launch vehicle in a carefully controlled formation. The individual satellites will receive both direct and reflected signals from GPS satellites. Direct signals pinpoint the location of each spacecraft; reflected signals measure surface roughness, from which wind speed is derived. The new data will give scientists a detailed look at the key air–sea interaction processes that take place near the inner core of tropical storms, which change rapidly and play large roles in the genesis and intensification of hurricanes. Please turn to page 4 of this issue to learn much more about CYGNSS; information is also available at *http://www.cygnss-michigan.org*.

The Suomi National Polar-orbiting Partnership (NPP) recently celebrated the fifth anniversary of its launch on October 28, 2016. Suomi NPP is a bridge to NOAA's next generation Joint Polar Satellite System (JPSS) weather satellites. The JPSS-1 satellite is scheduled to launch in 2017. Suomi NPP also helps extend the measurement records for environmental variables that have been made by the research instruments aboard the core NASA Earth Observing System missions (Terra, Aqua, and Aura) since their respective launches in 1999, 2002, and 2004, as well as data from earlier NOAA operational platforms and NASA research satellites to help create multi-decadal environmental records.

Data from the five Suomi NPP instruments are used to generate dozens of atmosphere, oceans and land environmental data products. These include: atmospheric temperature/moisture profiles; clouds; hurricane intensity and position; thunderstorms, tornado potential; ice detection; precipitation and floods; dense fog; volcanic ash; fire and smoke; sea surface temperature and ocean color; sea ice extent and snow cover/depth; polar satellite-derived winds; vegetation greenness indices and health; ozone; and oil spills.

Data from Suomi NPP are transmitted to a receiving station in Svalbard, Norway and then routed to

[2] Earth Venture (EV) Class solicitations are broken down into three categories: Missions, Instruments, and Suborbital (EVM, EVI, and EVS respectively). CYGNSS is classified as EVM-1; GEDI, mentioned later, was one of two EVI-2 selections. Learn more at *https://science.nasa.gov/about-us/smd-programs/earth-system-science-pathfinder*.

the NOAA Satellite Operations Facility, in Suitland, MD. As is the case for Terra, Aqua, and OMI on Aura, users can also use direct broadcast antennas to quickly access Suomi NPP observations to support critical missions. Turn to page 22 to learn more about the evolution of direct broadcast/direct readout capabilities, the specific role of NASA's Direct Readout Laboratory, and a summary of the ninth NASA Direct Readout Conference which took place June 21-24, 2016 in Valladolid, Spain. To learn more about Suomi NPP, visit *https://jointmission.gsfc.nasa.gov/suomi.html*.

The International Space Station Rapid Scatterometer (ISS-RapidScat) instrument has ended operations due to power distribution problems. The mission, launched in September 2014 to provide near-real-time monitoring of ocean winds, recently passed its original decommissioning date. The ISS-RapidScat instrument was a cost effective and timely replacement for the SeaWinds scatterometer on the QuikSCAT satellite. The less than two year build time was achieved by adapting spare parts from the QuikSCAT mission (launched in 1999 and fully active until 2009 when its antenna stopped spinning). ISS-RapidScat was the first continuous Earth-observing instrument specifically designed and developed to operate on the ISS exterior (followed by CATS in early 2015, with SAGE III and LIS scheduled for launch to the ISS in 2017). With the ISS's precessing orbit, RapidScat was the first space-borne scatterometer to observe wind evolution throughout the course of a day. ISS-RapidScat was a partnership between JPL, the ISS Program Office, and the NASA Earth Science Division.

Previously we reported on the status of the aging GRACE mission,[3] and how current mission operation efforts are focused on extending mission life to allow for overlap with the GRACE Follow-On (GRACE-FO) mission, which is scheduled for launch in late 2017 or early 2018. Construction is now complete on the first of two GRACE-FO satellites; the second will be ready shortly. The satellites, built by Airbus Defense and Space at its manufacturing facility in Friedrichshafen, Germany, will spend the next several months undergoing testing at the IABG test center in Ottobrunn, near Munich. The multinational mission operations team at GSOC, GFZ, JPL, and UT/CSR, together with industry support, continues to work towards minimizing any data gap that might occur between that of the GRACE mission and the beginning of GRACE-FO.

I would also like to draw attention to two other articles in this issue. The Global Ecosystem Dynamics Investigation (GEDI) mission is one of two instruments chosen from the second Earth Venture Instrument (EVI-2) Pathfinder Program.[4] GEDI is a multibeam lidar that will be installed on the Japan Experiment Module–Exposed Facility (JEM-EF) onboard the ISS in late 2018 and will provide Earth's first comprehensive and high-resolution dataset of ecosystem structure. Data from GEDI will advance our ability to characterize the effects of changing climate and land use on ecosystem structure and dynamics.

Data from GEDI is now in Phase C of its development meaning that design and development is now underway. The GEDI Science Team held its second Science Team Meeting September 21-23, 2016 at GSFC. The main objectives of the meeting were to provide updates on engineering and mission progress, reports on the status of science algorithms, and to review mission calibration and validation activities, both internal to the GEDI science team as well as collaborative and cross-mission activities such as the AfriSAR campaign.[5] Please turn to page 31 to learn more about GEDI and the details of the Science Team Meeting.

This issue also contains a report on a partnership between NASA's DEVELOP Program and the U.S. National Park Service (NPS). This year marked the one hundredth anniversary of the NPS. During the 2016 summer term, DEVELOP participants and NPS representatives collaboratively conducted nine projects using a suite of NASA's Earth observations to address environmental issues impacting national parks and NPS Inventory and Monitoring Programs in 22 states. The nine projects identified methods to monitor a variety of attributes such as vegetation health, drought, species habitat extent, forest disturbances, invasive species, air-quality parameters, and archaeology sites. Turn to page 14 of this issue to learn more about the DEVELOP–NPS partnership and the specific projects that were conducted.

Once again, we close-out another busy year for *The Earth Observer*. We can all take pride that newsletter articles—and content shown at other outreach venues such as the annual AGU exhibit (see the Announcement on page 44 of this issue)—have highlighted the many ways that NASA Earth Science research and applications have benefited society and help us better understand the changing environment and climate of the planet we call home. We could not have done this without your continued support and interest. On behalf of *The Earth Observer* staff and the Earth Science Division, our sincere thanks to everyone who contributed content to this year's newsletter and exhibit activities, and best wishes to all for the year ahead. ■

[3] See Editorial of the March–April 2016 issue of *The Earth Observer* [**Volume 28**, **Issue 2**, pp. 2-3].

[4] The other instrument chosen was the ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS).

[5] The European Space Agency launched the first part of the AfriSAR campaign in Gabon, Africa in July 2015, collecting radar and field measurements of the country's forests. NASA and the German Aerospace Center [Deutsches Zentrum für Luft- und Raumfahrt (DLR)] joined the second leg of the campaign.

Eight Microsatellites, One Mission: CYGNSS

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In December 2016, the Cyclone Global Navigation Satellite System (CYGNSS) will become NASA's first satellite mission to measure ocean surface winds in the inner core of tropical cyclones, including regions beneath the eyewall and the intense inner rainbands that could not previously be measured from space.

Introduction

Tropical cyclones are amongst the most destructive of nature's forces, annually affecting the lives and livelihoods of millions around the globe. Several hazards are associated with tropical cyclones including very heavy rainfall, damaging winds, inland flooding, storm surge, and even tornadoes. The National Oceanic and Atmospheric Administration (NOAA) National Hurricane Center has noted that Hurricane Katrina was the costliest—and one of the deadliest—hurricanes in U.S. history. Much of the catastrophic damage that was caused by the storm has been attributed to the wind-generated storm surge that exceeded 20 ft (6 m) above high tide across parts of the central Gulf Coast as the storm moved onshore. The intensity of Hurricane Katrina's winds varied between Category 1 (winds 74 to 94 mph) and Category 5 (winds >155 mph) as the storm moved through the Gulf of Mexico and toward the Gulf Coast during the period of August 26-29, 2005. The ability to monitor and predict the rapid changes in hurricane intensity such as those observed with Katrina is critical to hurricane forecasters, hydrologists, emergency managers, and other community leaders who together are responsible for protection of the health and welfare of coastal communities.

The accuracy of tropical cyclone track forecasts has improved by approximately 50% since 1990, largely as a result of improved weather forecast models and inclusion of satellite-derived data by these models. By contrast, during that same period, there has been very little improvement in the accuracy of intensity (peak sustained wind speed) forecasts. The limited improvement in intensity forecasts is likely the result of inadequate observations of the storm's inner core, including the eyewall and the intense inner rainbands of the storm.

In December 2016, the Cyclone Global Navigation Satellite System (CYGNSS) will become NASA's first satellite mission to measure ocean surface winds in the inner core of tropical cyclones, including regions beneath the eyewall and the intense inner rainbands that could not previously be measured from space.[1] These measurements will help scientists to obtain a better understanding of what causes variations in tropical cyclone intensity, thereby improving our ability to forecast tropical cyclones[2] such as Hurricane Katrina.

Hurricane Formation

The two key ingredients for hurricane formation are warm ocean surface water and light winds blowing in roughly the same direction at all levels of the atmosphere. The tropical (between the Equator and 5° N and S latitudes) and subtropical latitudes (between 5° and 30° N and S latitudes) of Earth are the most likely areas to offer both of these conditions consistently. In the Northern Hemisphere, most hurricanes form from late August through mid-October, when the ocean water is warmest, providing the warm and humid environment needed to produce clusters of thunderstorms. When *vertical wind shear* is minimal—meaning that winds are light and do not change direction with

[1] *The Earth Observer* first reported on the CYGNSS mission in the May-June 2013 issue [**Volume 25**, **Issue 3**, pp. 12-21], titled "NASA Intensifies Hurricane Studies with CYGNSS."

[2] In the Atlantic, Caribbean, and Central Pacific, tropical cyclones are called hurricanes, while in the Western Pacific they are called typhoons. In the Southern Hemisphere they are simply called cyclones.

height—these thunderstorms begin to grow in height and intensity. The heat released by the formation of these thunderstorms produces conditions which lead to the lowering of atmospheric pressure at the surface. As a result, ocean surface winds begin to blow toward the center of low pressure. In the Northern Hemisphere, hurricane winds rotate counterclockwise around a center of low atmospheric pressure, called the *eye*. Conversely, in the Southern Hemisphere, the rotation is clockwise. The eye of the storm is characterized by *subsiding* (i.e., sinking) air, cloudless skies, and very light winds. Surrounding the eye is a ring of intense thunderstorms that produce heavy rainfall and strong winds, known as the *eyewall*. The eyewall region of the storm is where the tallest and strongest thunderstorms are found, along with the strongest surface winds.

To describe the CYGNSS mission, we will first provide some historical background on how NASA has observed ocean surface winds from space, provide details of the mission, the eight-microsatellite observatories, and planned data acquisition. Finally, we will discuss how the data may be used to benefit of society, given the potentially harmful effects of the storms under study.

A Historical Perspective on Why We Need to Measure Ocean Surface Winds from Space

According to the World Meteorological Organization, over 10,000 weather stations on land provide (at least) three-hourly observations of meteorological conditions at or near Earth's surface, including: cloud cover, atmospheric pressure, temperature, precipitation, and wind direction and speed. Despite the extensive characterization of meteorological conditions over land, relatively limited observations are available to describe meteorological conditions over the ocean—which covers approximately 70% of Earth's surface! While ship- and buoy-based measurement platforms provide some information over the ocean surface, satellite-based measurements play a critical role filling in the gaps and providing a truly global characterization of meteorological conditions, including ocean surface wind direction and speed.

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Technical Underpinnings

Around the time of World War II, several nations began to experiment with radar technology as part of their defense systems. The noise observed in the received signals during these early surface-based radar measurements over ocean surfaces was found to be the result of winds over the ocean. This finding opened new avenues of technology and research, and resulted in the development of a number of radar remote sensing systems designed specifically to measure ocean surface winds.

Since the 1970s, NASA has carried out a series of missions that have focused on monitoring winds over the ocean surface from space—see **Figure 1**—based on *scatterometry,* whereby the instrument sends a pulse of microwave energy towards the Earth's surface and measures the intensity of the return pulse that reflects back from the surface, and *microwave radiometry*, whereby the instrument measures natural thermal emission by the wind-driven ocean foam. The first attempt to measure winds from space occurred when NASA built a "technology demonstration" instrument that flew onboard NASA's Skylab—the United States' first space station—from 1973 to 1979. This successful demonstration showed that remotely sensed measurements of ocean surface winds were indeed possible using space-based scatterometers. NASA launched its second scatterometer, the SeaSat-A Scatterometry System (SASS), onboard the SeaSat-A satellite in 1978. SeaSat-A also carried the first ocean wind radiometer, the Scanning Multichannel Microwave Radiometer (SMMR). While the mission lifetime was limited (it only operated from June to October of that year, due to a power system failure), SASS and SMMR were able to confirm that space-based scatterometry and radiometry were effective tools for making accurate ocean surface wind measurements.

Increasing Technological Sophistication

It was not until nearly twenty years later, in August 1996, that NASA would launch its next scatterometry mission, called the NASA Scatterometer (NSCAT), onboard

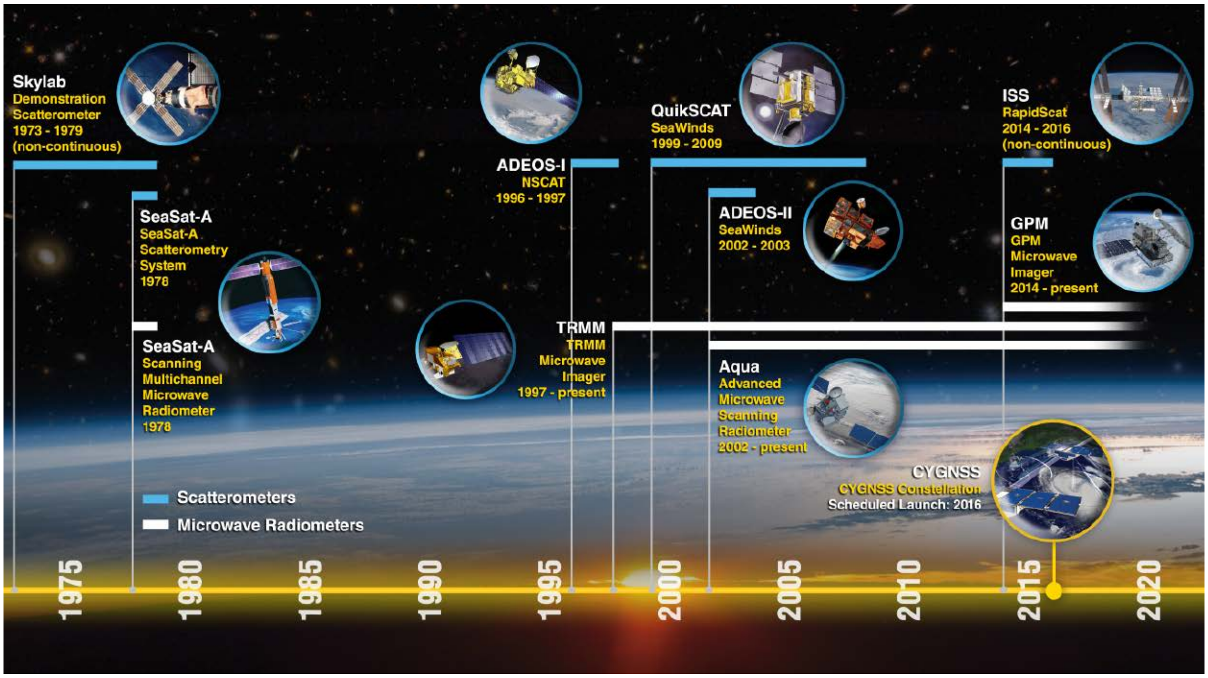

Figure 1. Timeline of NASA scatterometry and microwave radiometry missions. **Image credit:** NASA

Since the 1970s, NASA has carried out a series of missions that have focused on monitoring winds over the ocean surface from space based on scatterometry...and microwave radiometry.

the Japan Aerospace Exploration Agency's (JAXA) Advanced Earth Observing Satellite (ADEOS-I). NSCAT operated continuously at a microwave frequency of 13.995 GHz, using backscatter data from the instrument's radar to generate 268,000 globally distributed *wind vectors* (i.e., both wind speed and direction) each day. Every two days, NSCAT measured wind speeds and directions over at least 90% of ice-free ocean surfaces at a resolution of 31 mi (50 km). Like some of its predecessors, the mission was short-lived; the solar panels on the ADEOS-I satellite ceased to function properly in July 1997, ending the mission less than a year following its launch.

Following the end of the ADEOS-I mission, NASA's Jet Propulsion Laboratory built two identical SeaWinds scatterometry instruments. The first launched in 1999 on NASA's Quick Scatterometer (QuikSCAT) satellite. SeaWinds used a rotating dish antenna to send microwave pulses at a frequency of 13.4 gigahertz down to Earth's surface. The characteristics of the returned signal were used to estimate surface wind speed and direction with an accuracy of ±2 m/s (4.5 mph) and ± 20° respectively, at a resolution of 25 km (~15.5 mi). The second SeaWinds instrument launched on JAXA's ADEOS-II satellite in 2002; however, it suffered an eerily similar fate to its predecessor: the spacecraft failed less than a year after launch in October 2003. Meanwhile, the SeaWinds instrument on the earlier QuikSCAT remained fully operational until 2009, when a bearing in the radar antenna's spin mechanism failed. While the instrument performance was not affected by the spin mechanism failure, the scatterometer's coverage area was—and remains—significantly reduced. Data from SeaWinds, however, remain important for calibrating other scatterometers currently in orbit.

To help overcome the loss of functionality of both SeaWinds instruments, NASA refurbished a QuikSCAT *engineering model*—a copy of the instrument built specifically for testing—to fly on the International Space Station (ISS). The ISS Rapid Scatterometer (ISS-RapidScat), which was installed on the station in 2014. Like QuikSCAT, ISS-RapidScat measured both wind speed and direction over the ocean surface at a resolution of approximately 15.5 mi (25 km). On November 28, 2016, NASA announced the end of the ISS-RapidScat mission.[3]

[3] On August 19, 2016, a power distribution unit for the space station's Columbus module failed, resulting in a power loss to ISS-RapidScat. Later that day, as the mission operations team from NASA/Jet Propulsion Laboratory attempted to reactivate the instrument, one of the outlets on the power distribution unit experienced an electrical overload. In the following weeks, multiple attempts to restore ISS-RapidScat to normal operations were not successful, including a final attempt on October 17.

More Data! We Need More Data!

While radar scatterometers have been used to provide high-resolution measurements of ocean-surface wind speed and direction, they cannot observe the inner core of a hurricane because it is obscured by intense precipitation in the eyewall and inner rainbands, for reasons to be discussed later. In addition, the rapidly evolving stages of the tropical cyclone life cycle occur on relatively short timescales (i.e., on the order of hours or days), and are poorly sampled by conventional polar-orbiting, wide-swath satellite imagers such as QuikSCAT and ADEOS-II that generally pass over a particular spot on Earth, at most every other day. It is in response to the lack of such data and the need for consequent understanding of the phenomena being measured, that CYGNSS came into being. How and why this response developed will be discussed in the next section.

CYGNSS will collect the first frequent, space-based measurements of surface wind speeds in the inner core of tropical cyclones using a constellation of eight microsatellites.

CYGNSS Mission Overview

CYGNSS is a NASA Earth System Science Pathfinder Mission. As with many such complex missions, different aspects are addressed by different teams, associated with different organizations—see *CYGNSS:* A *Tightly Knit Partnership* on the next page. CYGNSS will collect the first frequent, space-based measurements of surface wind speeds in the inner core of tropical cyclones using a constellation of eight microsatellites.[4] The microsatellite observatories will provide nearly gap-free Earth coverage owing to an orbital inclination of approximately 35° from the equator, with a mean (i.e., average) revisit time of seven hours and a median revisit time of three hours. These orbital parameters will allow CYGNSS to measure ocean surface winds between 38° N and 38° S latitude, which—notably—includes the critical latitude band for tropical cyclone formation and movement—see **Figure 2**.

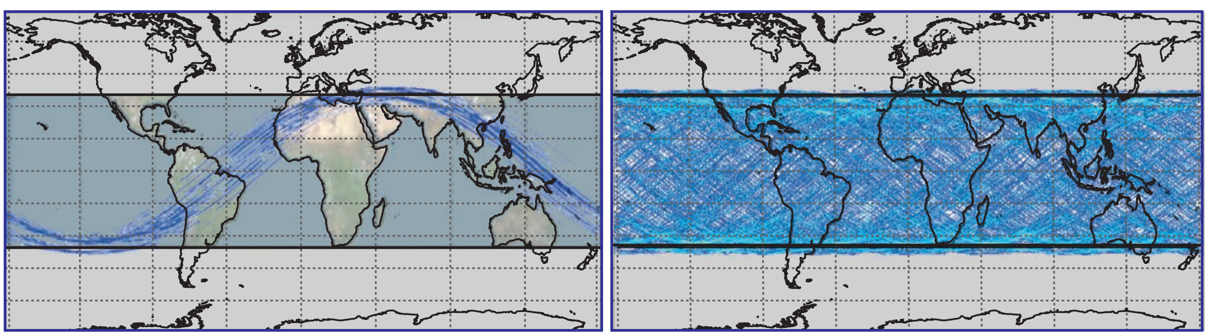

Figure 2. A benefit of using a constellation of microsatellite observatories is that they will pass over the same spot on the ocean more frequently than a single satellite would, resulting in better resolution of changes in the ocean's surface on short time scales. These maps show sample ground tracks between 35° N and 35° S latitude from the CYGNSS microsatellite observatories for 95 minutes [*left*] and a full day [*right*]. **Image credit:** University of Michigan

Technology, Measurements, and Science

The goal of the mission is to study the relationships between ocean surface roughness (from which wind speed is derived), moist atmospheric thermodynamics, radiation, and convective dynamics in the inner core of a tropical cyclone. This will allow scientists to determine how a tropical cyclone forms, whether or not it will strengthen and—if so—by how much. The successful completion of these goals will allow the mission to contribute to the advancement of tropical cyclone forecasting and tracking methods.

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To reach this goal, CYGNSS will measure the ocean surface wind field with unprecedented temporal resolution and spatial coverage, under all precipitating conditions, and over the full dynamic range of wind speeds experienced in a tropical cyclone. The mission will accomplish this through an innovative combination of all-weather performance global positioning system (GPS)-based scatterometry, with the sampling

[4] Microsatellites—also called small satellites, or smallsats—are satellites of low mass and size, usually under 500 kg (1100 lbs). Each of the CYGNSS satellites will weigh 28.9 kg (63.7 lbs).

CYGNSS: A Tightly Knit Partnership

Funded by NASA's Science Mission Directorate and managed by NASA's Langley Research Center, the University of Michigan (UM) has been selected to serve as the lead institution for CYGNSS, while the Southwest Research Institute (SwRI) has primary responsibility for production of the CYGNSS microsatellite observatories. The UM Space Physics Research Laboratory collaborated with SwRI on the design, fabrication, and development of the microsatellite observatories. NASA's Launch Services Program at the agency's Kennedy Space Center is responsible for management and oversight of the Pegasus XL launch services.

The UM Climate and Space Department will house the CYGNSS Science Operations Center (SOC), which is responsible for constellation calibration/validation activities, routine science data acquisition and special requests, and data processing and storage. The CYGNSS Mission Operations Center (MOC) will be located within SwRI's Planetary Science Directorate in Boulder, CO. The MOC will be responsible for mission planning, flight dynamics, and command and control tasks for each of the microsatellite observatories in the constellation. The data from CYGNSS will be made freely available via the NASA/Jet Propulsion Laboratory's Physical Oceanography Distributed Active Archive Center (PODAAC).

Other primary partners include: Sierra Nevada Corporation, which will provide the deployment module for the microsatellite observatories; Surrey Satellite Technology, U.K., which will be responsible for the Delay Doppler Mapping Instrument (described below); and Orbital ATK, which will provide the launch vehicle for the mission (Pegasus XL rocket).

properties of a dense constellation of eight microsatellite observatories. Two aspects of the CYGNSS mission make it unique. One is that it will be NASA's first mission to perform surface remote sensing using an existing Global Navigation Satellite System (GNSS)—a satellite constellation that is used to pinpoint the geographic location of a user's receiver anywhere in the world.[5] The other is that it will be the first ever mission which uses a constellation of small satellites to improve the temporal sampling of the Earth environment.

Two aspects of the CYGNSS mission make it unique. One is that it will be NASA's first mission to perform surface remote sensing using an existing Global Navigation Satellite System (GNSS)...The other is that it will be the first ever mission which uses a constellation of small satellites to improve the temporal sampling of the Earth environment.

Unlike radar scatterometers (e.g., ISS-RapidScat) that emit microwave radar pulses and receive their backscattered signals, CYGNSS's eight microsatellites will only receive scattered GPS signals. Additionally, the microwave radar pulses used by existing radar scatterometers degrade when passing through the intense rainfall typically observed within hurricane eyewalls, thus limiting their utility in measuring the wind speeds in this critical region of the storm. The scattered GPS constellation signals, on the other hand, operate at a much lower microwave frequency, one that is able to penetrate the thick clouds and precipitation around the eyewall; thus, they provide the first opportunity to remotely measure inner-core wind speeds.

The CYGNSS Microsatellite Observatories

Prior to full deployment, each CYGNSS observatory will be approximately 20L x 23W x 8.6H in (51 x 59 x 22 cm). In orbit, each observatory will deploy solar panels such that its final width will reach a wingspan of 63 in (160 cm), incidentally typical of a full-grown swan. The observatories will use under 60 W of power (less than an average household incandescent light bulb), and weigh 28.9 kg (63.7 lbs). The solar panels will be used to collect incoming radiation from the sun to provide energy to recharge the onboard batteries that power the observatories.

The measurements employed by the CYGNSS observatories will rely on characterizing the signal propagation from the existing GPS constellation, located approximately 12,427 mi (20,000 km) above Earth's surface, as well as on the nature of the scattering

[5] A number of GNSS systems are currently in operation, including: the United States' Global Positioning System (GPS), the European Galileo, the Russian Federation's Global Orbiting Navigation Satellite System (GLONASS), and the Chinese BeiDou system. CYGNSS will use the U.S. GPS constellation.

of these signals by the ocean surface. The observatories will each carry a Delay Doppler Mapping Instrument (DDMI), which consists of a Delay Mapping Receiver (DMR) electronics unit, two nadir- (i.e., downward-) pointing antennas to collect the GPS signals scattered off of the ocean surface, and a single zenith- (i.e., upward-) pointing antenna to collect the GPS signals, directly. The DMR on each observatory consists of a single, traditional, GPS navigation receiver (to support standard GPS geolocation capability, navigation, and timing functions), and four customized GPS receivers to perform the remote sensing signal processing. The scattered GPS signals from the ocean surface received by each of the four GPS receivers will be used to generate Delay Doppler Maps (DDMs), from which ocean surface wind speeds are retrieved—see *Delay Doppler Maps* on page 10. Each observatory will generate four DDMs per second, resulting in 32 simultaneous wind measurements by the complete constellation.

Photo. Pegasus XL expendable rocket affixed to the bottom of the L-1011 Stargazer. **Image credit:** NASA

Getting CYGNSS into Space: Launch and Deployment

The CYGNSS constellation is scheduled for launch on a single vehicle in December 2016 from NASA's Kennedy Space Center at Cape Canaveral, Florida. The launch vehicle will be an Orbital ATK Pegasus XL expendable rocket. Affixed to the bottom of an Orbital ATK L-1011 Stargazer airliner (see **Photo**), the Pegasus rocket will be carried to an altitude of approximately 40,000 ft (12.4 km). Upon reaching this altitude, the aircraft will release the Pegasus rocket, which will then ignite and boost the eight observatories, attached to a Sierra Nevada Corporation deployment module (DM), into low Earth orbit (LEO) approximately 317 mi (510 km) above Earth's surface. The eight observatories will be arranged on the DM in two tiers, with four observatories in each tier—see **Figure 3**. The observatories will be released from the DM in a sequence of four, oppositely positioned microsatellite observatory pairs, which will ensure the stability of the DM during the release sequence.

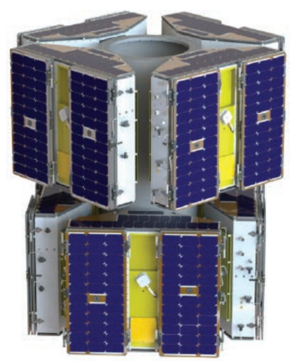


Figure 3. Deployment module that will perform the sequential release of four pairs of microsatellite observatories. **Image credit:** Sierra Nevada Corporation

Ground Segment

To control the observatories and receive and distribute data from the them, the CYGNSS mission ground segment consists of a Mission Operations Center (MOC), located at the Southwest Research Institute's Planetary Science Directorate in Boulder, CO; a Science Operations Center (SOC), located at the University of Michigan's Space Physics Research Laboratory in Ann Arbor, MI; and a Ground Data Network, operated by Swedish Space Corporation (SSC) Space U.S., Inc.'s Universal Space Network, consisting of existing PrioraNet ground stations in South Point, HI; Santiago, Chile; and Western Australia, approximately 248 mi (400 km) south of Perth—see **Figure 4**. Each of these components will be discussed in more detail, later.

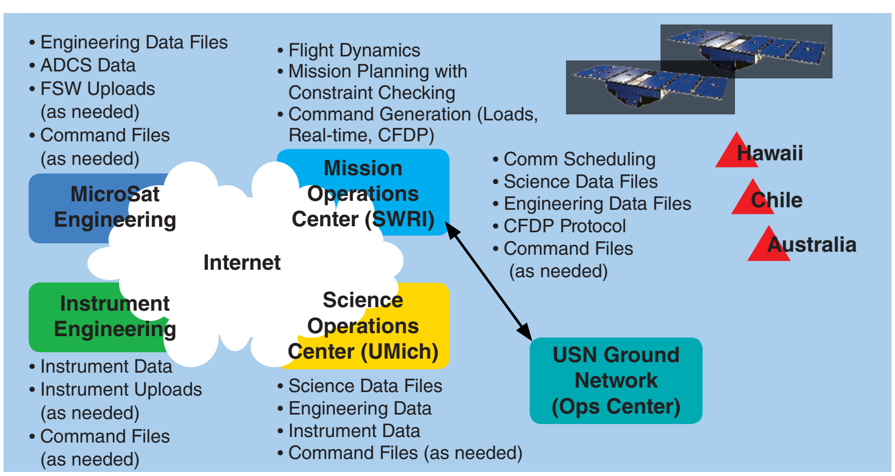
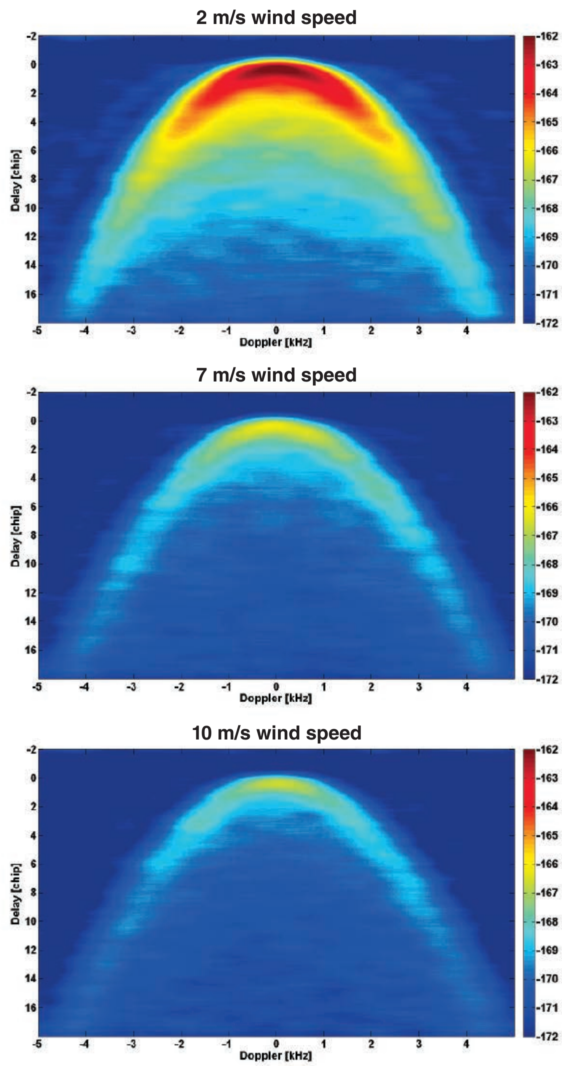


Figure 4. Diagram showing an overview of the components of the CYGNSS ground system. **Image credit:** NASA

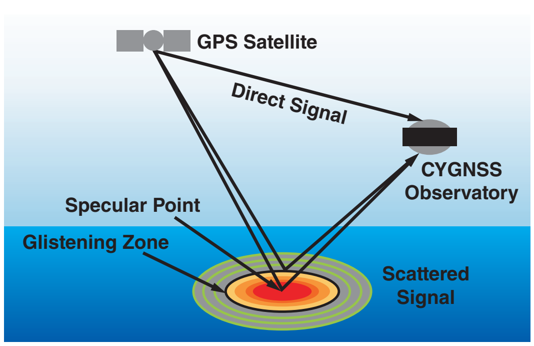
Delay Doppler Maps

The color scale of a DDM denotes the power in the signals scattered by the ocean surface and received by the DDMI (see diagram below), where darkest shades indicate the strongest scattering. The y-axis (see graphs, right) represents the time delay between the direct and scattered received signals (from the GPS and ocean, respectively), while the x-axis represents the shift in frequency between the direct and scattered received signals. The two axes are normalized with respect to the delay and Doppler shift at the *specular point*, the spot on the ocean surface where the scattered signal strength is largest (see three graphs, right).

Wind speed is estimated from the DDM by relating the region of strongest scattering (the darkest region) to the ocean surface roughness. A smooth ocean surface will reflect a GPS signal directly up toward the CYGNSS observatory, producing a strong received signal. A roughened ocean will result in more diffuse scattering of the signal in all directions (called the *glistening zone*), resulting in a weaker received signal. Therefore, strong signals at the receiver represent a smooth ocean surface and calm wind conditions, while weak received signals represent a rough ocean surface and high wind speeds. The exact relationship between received signal strength and wind speed is provided by the CYGNSS wind speed retrieval algorithm.



[*Above*] Example of Delay Doppler Maps for 2, 7, and 10 m/s (~5, 16, 22 mi/hr) wind speeds [*top to bottom*]. The images show how progressively stronger wind speeds, and therefore progressively rougher sea surfaces, produce a weaker maximum signal (at the top of the "arch") and a scattered signal along the arch that is closer in strength to the maximum. A perfectly smooth surface would produce a single dark spot at the top of the arch. **Image credit:** University of Michigan



[*Left*] This diagram shows the direct signal is transmitted from the orbiting GPS satellite and received by the single zenith-pointing- (i.e., top-side-) antenna, while the scattered GPS signal scattered off the ocean surface is received by the two nadir-pointing- (i.e., bottom-side-) antennas. **Image credit:** University of Michigan

Mission Operations Center

Throughout the mission, the MOC is responsible for mission planning, flight dynamics, and command and control tasks for each of the observatories in the constellation. The MOC also coordinates operational requests from all facilities and develops long-term operations plans. Primary MOC tasks include:

- coordinating activity requests;
- scheduling ground network passes;
- tracking and adjusting the orbital location of each observatory;
- providing trending microsatellite data;
- creating real-time command procedures or command loads required to perform maintenance and calibration activities;
- maintaining configuration of on-board and ground parameters for each observatory;
- maintaining the Consultative Committee for Space Data Systems (CCSDS) File Delivery Protocol [CFDP] ground processing engine; and
- collecting and distributing engineering and science data.

Science Operations Center

The SOC will be responsible for the following items related to calibration/validation activities, routine science data acquisition and special requests, and data processing and storage. Primary SOC tasks include:

- supporting DDMI testing and validation both prelaunch and on-orbit;
- providing science operations planning tools;
- generating instrument command requests for the MOC;
- processing Level-0 through -3 science data; and
- archiving Level-0 through -3 data products (see *Science Data Products*, below), DDMI commands, code, algorithms, and ancillary data at NASA's Physical Oceanography Distributed Active Archive Center (PO.DAAC), located at the NASA/Jet Propulsion Laboratory.

Ground Data Network

CYGNSS contracted with SSC Space U.S., Inc.'s Universal Space Network (USN) to handle ground communications because of their extensive previous experience with missions similar to CYGNSS. Each of the observatories in the CYGNSS constellation will be visible to the three ground stations (Hawaii, Chile, Australia) within the USN for periods that average between 470 and 500 seconds of visibility per pass. Each observatory will pass over each of the ground stations six-to-seven times each day, thus providing a large pool of scheduling opportunities for communications passes. MOC personnel will schedule passes as necessary to support commissioning and operational activities. High-priority passes will be scheduled to support solar array deployment for each observatory upon commissioning.

For all subsequent stages, the MOC schedules nominal passes for the USN stations for each observatory in the constellation per the USN scheduling process. Each observatory can accommodate gaps in contacts with storage capacity for greater than 10 days worth of data, with no interruption of science activities.

Each of the observatories in the CYGNSS constellation will be visible to the three ground stations (Hawaii, Chile, Australia) within the USN for periods that average between 470 and 500 seconds of visibility per pass. Each observatory will pass over each of the ground stations six-to-seven times each day, thus providing a large pool of scheduling opportunities for communications passes.

Science Data Products

The CYGNSS mission will produce three levels of science data products for public distribution through PO.DAAC. Data from CYGNSS will be freely available for download at *http://podaac.jpl.nasa.gov*. The maximum data latency from spacecraft downlink to PO.DAAC availability is six days for all three data levels. To learn about the plans for calibration and validation efforts, see *CYGNSS Calibration and Validation Objectives,* below.

*The CYGNSS mission will produce three levels of science data products for public distribution through PO.DAAC. Data from CYGNSS will be freely available for download at **http://podaac.jpl.nasa.gov**.*

Level-1 Products: Delay Doppler Maps

The goal of Level-1 science data processing is to produce DDMs of calibrated bistatic radar crosssections. All Level-1 science data products are provided at a time resolution of 1 Hertz.

Level-2 Products: Wind Speed Retrieval and Mean Squared Slope

The Level-2 wind speed product is the spatially averaged wind speed over a ~9.7 x 9.7 mi^2 (25 x 25 km^2) region centered on the specular point. While the primary objective of the CYGNSS mission is to measure ocean surface winds, Level-1 products can also be related to the mean-square-slope (MSS) of the ocean surface, which is crucial for understanding physical processes at the air-sea interface.

Level-3 Products: Gridded Wind Speed and Mean Squared Slope

The Level-3 gridded wind speed product is derived from the Level-2 wind speeds by averaging them in space and time on a 0.2° x 0.2° latitude/longitude grid. Each Level-3 gridded wind file covers a one-hour time period for the entire CYGNSS constellation. The Level-3 MSS product is a similarly gridded version of the Level-2 MSS product.

CYGNSS Calibration and Validation Objectives

The calibration and validation objectives are to:

- verify and improve the performance of the sensor and science algorithms;
- validate the accuracy of the science data products; and
- validate the utility of CYGNSS wind products in the marine forecasting and warning environment.

For satellite ocean wind remote sensing, validation typically involves comparing measurements with numerical weather model wind fields. This allows a relatively large number of collocated comparisons to be obtained in a short amount of time. Since model winds are generally not reliable enough to properly validate very-low or very-high wind speeds, other comparison data are required. Validated wind speed data from satellite sensors, such as scatterometers, can be compared more directly and provide higher wind speed validation. Validation at the highest wind speeds in tropical cyclones will require utilizing data collected from aircraft-based measurements, such as GPS dropsondes, or other remote sensing equipment that might be onboard, such as the Stepped Frequency Microwave Radiometer or the High Altitude Imaging Wind and Rain Airborne Profiler that fly onboard National Oceanic and Atmospheric Administration (NOAA)'s Hurricane Hunter aircraft.

Another facet of the validation effort will include training forecasters at the NOAA National Hurricane Center (NHC) in Miami, FL, to use CYGNSS-derived wind retrievals. At the end of each hurricane season, the retrievals will be provided to the forecasters, so they can evaluate their effectiveness during postseason storm analysis. The objectives of this effort will be to evaluate the value of these data in the operational environment and to get validation feedback from forecasters. Experience has shown that viewing the data from a forecaster's perspective can reveal performance issues that can remain hidden in global statistics.

Conclusion: Definite Benefits to Society

CYGNSS will measure surface winds in the inner core of tropical cyclones, including regions beneath the eyewall and intense inner rainbands that could not previously be measured from space. These measurements will help scientists obtain a better understanding of what causes the intensity variations in tropical cyclones, such as those observed with Hurricane Katrina, as described earlier. The surface wind data collected by the CYGNSS constellation are expected to lead to:

- improved spatial and temporal resolution of the surface wind field within the precipitating core of tropical cyclones;
- improved understanding of the momentum and energy fluxes at the air-sea interface within the core of tropical cyclones and the role of these fluxes in the maintenance and intensification of these storms; and
- improved forecasting capabilities for tropical cyclone intensification.

Combined, these accomplishments will allow scientists and hurricane forecasters to provide improved advanced warning of tropical cyclone intensification, movement, and storm surge location and magnitude, thus aiding in the protection of human life and coastal community preparedness. ■

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Congratulations to AGU and AMS Award Winners!

The Earth Observer is pleased to recognize the following Earth scientists from NASA who will receive awards from the American Geophysical Union (AGU) and American Meteorological Society (AMS) at their annual meetings in December 2016 and January 2017, respectively.

AGU Winners

Kevin Murphy [NASA Headquarters—*Program Executive for Earth Science Data Systems*] has been selected to receive the AGU's 2016 *Charles S. Falkenberg Award*. The award recognizes an early- to middle-career scientist who has contributed to the quality of life, economic opportunities, and stewardship of the planet through the use of Earth science information and to the public awareness of the importance of understanding our planet.

Kevin Murphy **Photo credit:** Karen Michael

In the September–October issue of *The Earth Observer* [**Volume 28**, **Issue 5**, p. 29], we recognized **Brent Holben** and **Claire Parkinson** [both from NASA's Goddard Space Flight Center] as 2016 Fellows of the AGU.

To see the full list of AGU honorees, visit *honors.agu.org*.

AMS Winners

Cynthia Rosenzweig [NASA's Goddard Institute for Space Studies—*Senior Research Scientist*] italicize position title per usual has been selected to receive AMS's *Walter Orr Roberts Lecturer in Interdisciplinary Sciences for 2017* award for her innovative efforts in turning climate knowledge into action in support of environmentally-based decision making in agriculture, urban systems, and assessment.

Cynthia Rosenzweig **Photo credit:** International Food Policy Research Institute

To see the full list of AMS award winners, visit *https://www.ametsoc.org/ams/index.cfm/about-ams/ams-awards-honors/2017-award-winners-and-fellows.*

Addressing Environmental Issues in America's National Parks: A Collaboration Between NASA DEVELOP and the National Park Service

Lauren Childs-Gleason, DEVELOP National Program, lauren.m.childs@nasa.gov
Georgina Crepps, DEVELOP National Program, georgina.s.crepps@nasa.gov

During the 2016 summer term, DEVELOP participants and NPS representatives collaboratively conducted nine projects using a suite of NASA's Earth observations to address environmental issues impacting national parks and NPS Inventory and Monitoring Programs in 22 states.

Introduction

President Woodrow Wilson signed the "Organic Act" on August 25, 1916, and thereby established the U.S. National Park Service (NPS)—a new federal bureau in the Department of the Interior responsible for protecting the 35 national parks and monuments then managed by the department and those yet to be established. Currently, the NPS oversees 413 federal areas, covering more than 84 million acres (~131,250 mi^2) across all 50 U.S. states and multiple U.S. territories and holdings. The NPS cares for and safeguards America's natural, recreational, cultural, and historical areas of national significance and continues to preserve, unimpaired, a wide variety of federal locations—including national parks, monuments, seashores, historic sites, recreation areas, parkways, riverways, and scenic trails—for the public and future generations to enjoy.

The year 2016 marks the centennial celebration for the NPS, kicking off a second century of stewardship and public engagement. Over the past 100 years, the NPS has pioneered many efforts related to protecting and advocating for America's open spaces and the environment, as well as led the global park and preservation community.

One of the NPS's guiding principles focuses on incorporating research findings and new technologies into their activities to improve work practices, products, and services. This goal aligns well with NASA's DEVELOP National Program, which introduces decision makers (state and local government, federal agencies, international governments, non-governmental organizations, and private corporations) to the benefits of NASA's Earth observations through a series of 10-week feasibility projects. DEVELOP, part of NASA's Applied Sciences' Capacity Building Program, conducts pilot projects in which teams of participants (recent graduates, transitioning career professionals, and students) collaborate with organizations making environmental decisions to demonstrate how NASA's Earth observations can be integrated into decision-making processes. Earth observations are an increasingly important tool for monitoring national parks and resources due to the synoptic (i.e., large-scale) nature of the data and consistent temporal coverage. Such observations provide coverage of remote areas in parks that would be otherwise difficult and costly for park managers to access. These shared interests set the stage for a fruitful collaboration between DEVELOP and the NPS in celebration of the NPS's centennial.

During the 2016 summer term, DEVELOP participants and NPS representatives collaboratively conducted nine projects[1] using a suite of NASA's Earth observations to address environmental issues impacting national parks and NPS Inventory and Monitoring Programs[2] in 22 states. The nine projects identified methods to monitor a variety of attributes such as vegetation health, drought, species habitat extent, forest disturbances, invasive species, air-quality parameters, and archaeological sites.

Invasive Species Mapping

DEVELOP participants assigned to the *Southwest U.S. Ecological Forecasting* and *Northern Great Plains Ecological Forecasting* projects used NASA's Earth observations to map invasive species in the Northern Great Plains (specifically, Badlands

[1] The relationship between DEVLEOP and the NPS builds on a partnership that began in the summer of 2015 when DEVELOP engaged with the NPS Intermountain Regional Office who connected DEVELOP teams with NPS parks and Inventory and Monitoring Programs throughout the U.S.

[2] To learn more, visit *http://science.nature.nps.gov/im/about.cfm*.

National Park, Wind Cave National Park, and Jewel Cave National Monument), and Southwestern U.S. (specifically, the Bandelier National Monument, Big Bend National Park, Glen Canyon National Recreation Area, and Valles Caldera National Preserve). The two projects investigated identification methodologies for a variety of invasive species such as ravenna grass (*Saccharum ravennae*), giant reed (*Arundo donax*), Japanese brome (*Bromus japonicus*), and cheatgrass (*Bromus tectorum* L.)—all pictured below. Of particular interest to the NPS is cheatgrass—a widespread invasive annual brome grass (one of a cool-season lineage related to wheat) distributed throughout the western U.S. The presence of invasive bromes has led to a decrease in native plant diversity, reduced soil-water content, and alteration of fire regimes, leading to more-frequent and higher-intensity fires. Prior to the investigations, the current park management primarily used field observations to monitor species, requiring a significant investment in time, effort, and money.

Of particular interest to the NPS is cheatgrass—a widespread invasive annual brome grass (one of a cool-season lineage related to wheat) distributed throughout the western U.S.

The DEVELOP participants used data from the Operational Land Imager (OLI) on Landsat 8, the Thematic Mapper (TM) on Landsat 5, and the Moderate Resolution Imaging Spectroradiometer (MODIS) on Terra and Aqua, along with data from the Multispectral Instrument (MSI) on the European Space Agency's Sentinel-2, to capture the vegetation phenology of these invasive brome species, and created classified species distribution maps for the national parks involved in the two projects—see **Figure 1** for an example. Participants from both projects concluded that NASA's Earth observations can be a used to map the distributions of invasive species. Further, the participants suggested that, combined with *in situ* data, NASA's Earth observations can be used to forecast the spread of invasive species. The projects provided a foundation for the NPS to incorporate remote sensing into inventory and monitoring protocols for invasive bromes and to apply these methods to additional parks within their network.

For more information on these two projects, see *Invasive Species Mapping Projects* on the next page.

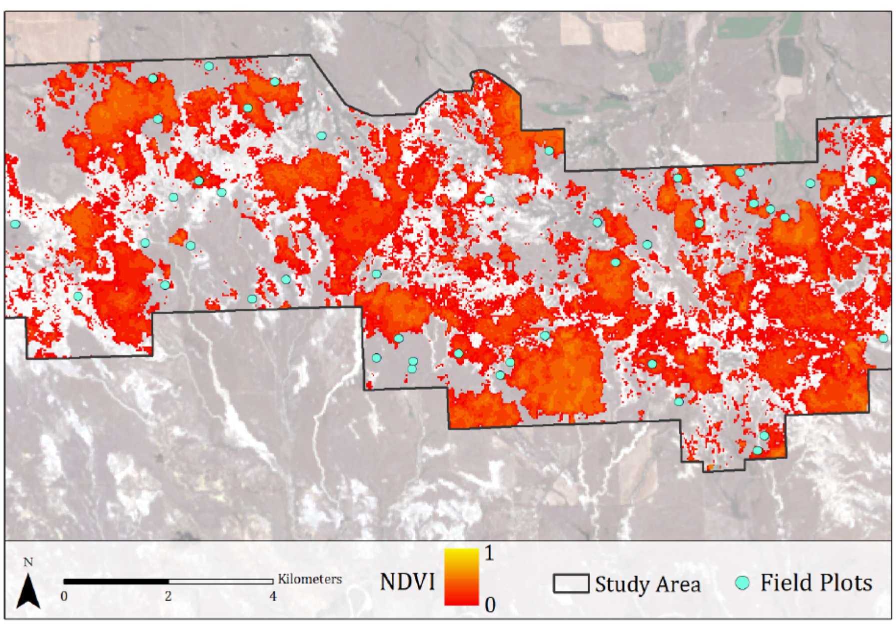
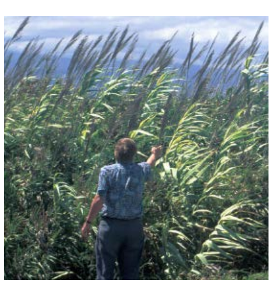


Figure 1. *Northern Great Plains Ecological Forecasting.* This map shows the difference between early- and late-season Normalized Difference Vegetation Index (NDVI) values, a measure of vegetation greenness, from April 11 - June 30, 2016 using data from Landsat 8 OLI. The results show areas that exhibit early vegetation phenology indicative of cheatgrass presence in the eastern portion of Badlands National Park. This allows land managers to remotely monitor cheatgrass extent and abundance over time, in addition to employing established field sampling protocols, to see how this invasive species impacts native grassland habitats. **Image credit:** NASA

Credit: Daderot

Ravenna Grass



Credit: U.S. Geological Survey

Giant Reed

Credit: Matt Lavin

Japanese Brome

Credit: Matt Lavin

Cheatgrass

Invasive Species Mapping Projects

Northern Great Plains Ecological Forecasting: Utilizing NASA Earth Observations to Map Temporal and Spatial Patterns of Annual Bromes in the Northern Great Plains to Develop a Management Plan for Invasive Species Control

- Video URL: *https://youtu.be/DpZoNXNZVyA?list=PLL8pCbx5gnDYUM084cxFpmidjGJJ1bOwf*
- Project Website URL: *https://develop.larc.nasa.gov/2016/summer/NorthernGreatPlainsEco.html*

Southwest US Ecological Forecasting: Mapping Invasive Species to Efficiently Monitor Southwestern National Park Areas

- Video URL: *https://youtu.be/iazbklzNPLI?list=PLL8pCbx5gnDYUM084cxFpmidjGJJ1bOwf*
- Project Website URL: *https://develop.larc.nasa.gov/2016/summer/SouthwestUSEco.html*

Landscape Disturbance Detection

Monitoring changing landscapes, including natural and anthropogenic disturbances, is central to the NPS's interests in preserving federal areas under its care. Three DEVELOP projects explored how the use of NASA's Earth observations and modeling efforts could support the NPS in monitoring a variety of landscape types including mangroves, forests, and critical species habitat.

Credit: Riandi/Flickr user

Florida Mangrove

The *Everglades Ecological Forecasting* project focused on improving mangrove-monitoring capabilities in Everglades National Park using the Google Earth Engine API[3] and data from TM and OLI to select, classify, and map mangrove-marsh regions (see photo left) between 1995 and 2015—see **Figure 2**. The goals of the project were to understand and assess the impacts of restoration and water diversion efforts and provide methods for continued monitoring to aid in creating forecasting models and to improve decision-support tools. Further, the project supported the NPS's activities to update the mangrove extent maps within select ecotones (transition regions between biomes) and provided a replicable process for the park staff to expand upon in coming years.

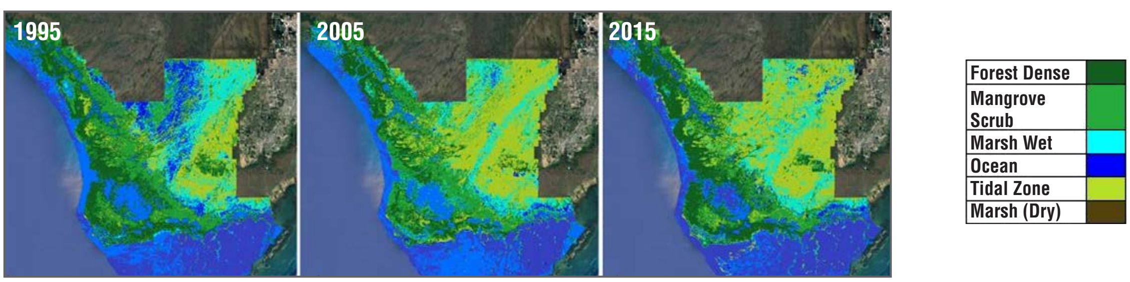


Figure 2. *Everglades Ecological Forecasting.* This series of images, created using data from Landsat 5 TM, Landsat 7 Enhanced Thematic Mapper Plus (ETM+), and Landsat 8 OLI with Top of Atmosphere Reflectance corrections, shows land-cover classifications for 1995 [*left*], 2005 [*center*], and 2015 [*right*] in Everglades National Park, specifically to identify mangrove extent over the last twenty years. Cloud cover was removed using an algorithm in the Google Earth Engine API, an important technique for further use of this methodology in temperate regions. Over the study period, mangroves have spread further inland, and changes in marshes and water reflect some of the management policies put into place to re-route freshwater back into the park. Mapping mangrove extent is difficult as these areas are usually hard to access and the process requires a lot of resources, including manpower. Park managers can use Earth-observing satellite data to save time and resources in the future. **Image credit:** NASA

Participants in the *Rocky Mountain National Park Agriculture* project mapped disturbances stemming from extreme weather events, changing climate, ecological issues, and direct human actions such as timber harvest in Rocky Mountain National Park

[3] API stands for application programming interface. Google Earth Engine is the most advanced cloud-based geospatial-processing platform in the world.

to classify historical harvest events on a landscape level using change detections and predictive classification models. This project integrated data from TM (on Landsat 4 and 5), Enhanced Thematic Mapper Plus (ETM+) on Landsat 7, and OLI, into the Landsat-based Detection of Trends in Disturbance and Recovery (LandTrendr)[4] algorithm to detect the magnitude, duration, and extent of past disturbances. The results allowed the participants to provide the NPS with labeled forest disturbance history maps to fill data gaps in past records. These products will inform NPS decision-making processes by addressing crucial knowledge gaps over the last 30 years and will enhance decision making in the future.

The *Eastern Idaho Disasters* project partnered with the Craters of the Moon National Monument and Preserve to develop a fire-susceptibility model using data from OLI and MSI to identify wildlife habitats for mule deer and greater sage-grouse (both pictured below, right) in the sagebrush-steppe ecosystem—see **Figure 3**. The team investigated the effects of differing spatial resolutions on the accuracy of the output models and applied weightings to model variables to discern fire behavior and habitat vulnerability. These models provide useful tools to better inform park and land managers in their decisions that are focused on preventing the loss of endangered species.

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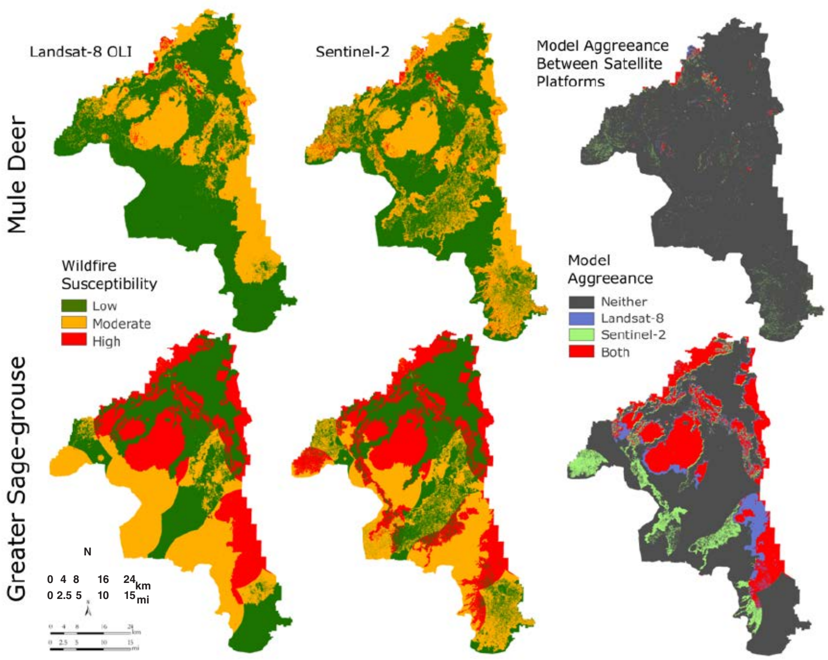

Figure 3. *Eastern Idaho Disasters.* These maps of Crater of the Moon National Monument (CRMO) display areas of mule deer [*top row*] and greater sage-grouse [*bottom row*] habitat that are susceptible to wildfires using data from Landsat 8 OLI [*left column*] and Sentinel-2 [*middle column*]. The maps show wildfire susceptibility as low, moderate, and high. The third column [*right*] compares the results for habitats that are highly susceptible to wildfire from both platforms. Areas that were classified as highly susceptible using only Landsat 8 OLI data are shown as blue, while areas that were classified as highly susceptible using only Sentinel-2 data are shown as light green. Areas found to be highly susceptible to wildfire by both platforms are red. Generally, the 10 m (~33 ft) Sentinel-2 model identified vegetation within the basalt formations of CRMO better than the 30 m (~98 ft) Landsat model, a likely benefit of its improved spatial resolution. However, the 30 m (~98 ft) Landsat model performed satisfactorily and is therefore a recommended choice as it is easier to acquire, use, and faster to process and analyze. **Image credit:** NASA

Mule Deer

Credit: U.S. Fish and Wildlife Service

Greater Sage-Grouse

Credit: Bob Wick/Bureau of Land Management

For more information on these three projects, see *Landscape Disturbance Detection Projects* on the next page.

[4] Algorithms in LandTrendr attempt to capture, label, and map the change of Earth's surface that Landsat has observed for more than four decades for use in science, natural resource management, and education. To learn more, visit *http://landtrendr.forestry.oregonstate.edu*.

Landscape Disturbance Detection Projects

Everglades Ecological Forecasting: Improving the Capacity of the Everglades National Park to Monitor Mangrove Extent using NASA Earth Observations

- Video URL: *https://youtu.be/XAr3hF-HkzQ?list=PLL8pCbx5gnDYUM084cxFpmidjGJJ1bOwf*
- Project Website URL: *https://develop.larc.nasa.gov/2016/summer/EvergladesEco.html*

Rocky Mountains Agriculture: Utilizing NASA Earth Observations to Reconstruct and Identify Historical Forest Disturbances in the Southern Rocky Mountains for Enhanced Forest Management

- Video URL: *https://youtu.be/-htgtUaxxxs?list=PLL8pCbx5gnDYUM084cxFpmidjGJJ1bOwf*
- Project Website URL: *https://develop.larc.nasa.gov/2016/summer/RockyMountainAg.html*

Eastern Idaho Disasters: Utilizing NASA Earth Observations to Identify Wildlife Habitat Areas Threatened by Heightened Wildfire Susceptibility for Improved Conservation and Management Practice

- Video URL: *https://youtu.be/fJN2Dq_4zKA?list=PLL8pCbx5gnDYUM084cxFpmidjGJJ1bOwf*
- Project Website URL: *https://develop.larc.nasa.gov/2016/summer/EasternIdahoDisasters.html*

Cultural Resource Preservation

The NPS is the steward of many important cultural resources, including cultural landscapes, archaeological resources, ethnographic resources, and historic and prehistoric structures. The NPS Cultural Resource Management Programs pursue activities that increase the information about cultural resources and ensure their preservation. In support of NPS's Intermountain Regional Office's Cultural Resources, two projects explored the use of NASA's Earth observations to identify and monitor cultural resources in Rocky Mountain National Park and Chaco Canyon National Park.

In support of NPS's Intermountain Regional Office's Cultural Resources, two projects explored the use of NASA's Earth observations to identify and monitor cultural resources in Rocky Mountain National Park and Chaco Canyon National Park.

The *Northern Great Plains Water Resources* project focused on the Rocky Mountain National Park and other national parks in the Intermountain Region of the northern U.S. Great Plains. Parks in this area are experiencing snow and ice melt due to changes in climate. As the persistent ice and snow cover (PISC) recedes, previously undiscovered archaeological sites are potentially uncovered driving the need for enhanced monitoring capabilities. The participants incorporated TM, ETM+, OLI, and temperature data from Oregon State University's PRISM[5] Climate Group to detect changes in PISC between 1995 and 2015. The results were used to identify decreasing glacier extent. NPS personnel can use such maps to develop techniques to mitigate the impacts of climate change on mountain cultural heritage resources through improved monitoring capabilities.

Participants from the *Chaco National Historical Park Cross-Cutting* project used data from OLI, Shuttle Radar Topography Mission (SRTM), and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) on Terra, along with Hyperspectral Thermal Emission Spectrometer (HyTES[6]) data, LANDFIRE[7] land cover data, and images from the U.S. Department of Agriculture (USDA) National Agriculture Imagery Program (NAIP) to identify spectral signatures of previously unknown Chacoan infrastructure and communities from 850 to 1150 AD. Remnants

[5] PRISM stands for Parameter-elevation Relationships on Independent Slopes Model.
[6] HyTES is an airborne thermal infrared imaging spectrometer that was developed to support the Hyperspectral Infrared Imager (HyspIRI) mission. To learn more, visit *http://hytes.jpl.nasa.gov*.
[7] LANDFIRE stands for Landscape Fire and Resource Management Planning Tools; it is a shared program between the wildland fire management programs of the U.S. Department of Agriculture Forest Service and U.S. Department of the Interior, providing landscape scale geospatial products to support cross-boundary planning, management, and operations. To learn more, visit *http://www.landfire.gov/about.php*.

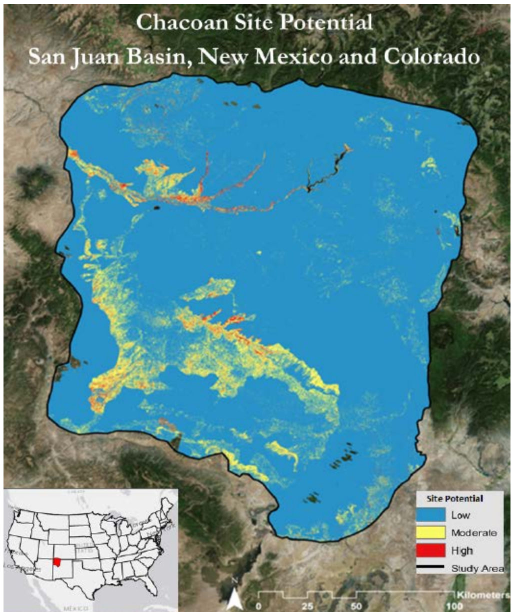

Figure 4. *Chaco National Historical Park Cross-Cutting.* This map shows areas that have a greater likelihood of containing Chacoan ruins. The different colors represent the potential (low to high) for the presence of Chacoan historical features. The study region, the San Juan Basin in southwestern New Mexico and southern Colorado, is outlined in black. **Image credit:** NASA

By identifying highly probable locations of unknown Chacoan sites the team was able to aid the NPS in determining sites at risk from infrastructure development, and support the preservation of our nation's historical resources.

of Chacoan architecture draw over 40,000 visitors a year to Chaco Cultural National Historic Park; however, many Chacoan roads and communities are located outside the boundaries of the park and are threatened by encroaching infrastructure. By identifying highly probable locations of unknown Chacoan sites—see **Figure 4**—the team was able to aid the NPS in determining sites at risk from infrastructure development, and support the preservation of our nation's historical resources.

For more information on these two projects, see *Cultural Resource Preservation Projects* below.

Cultural Resource Preservation Projects

Northern Great Plains Water Resources: Discovering Archeological Sites Utilizing NASA Earth Observations to Detect Changes in Snowpack Coverage in Intermountain National Parks

- Video URL: *https://youtu.be/woNfxnoD9FU?list=PLL8pCbx5gnDYUM084cxFpmidjGJJ1bOwf*
- Project Website URL: *https://develop.larc.nasa.gov/2016/summer/NorthernGreatPlainsWater.html*

Chaco Canyon Cross-Cutting: Utilizing NASA Earth Observations to Identify Chacoan Community Signature Profiles throughout the Chaco Canyon to Assist Preservation and Protection Strategies

- Video URL: *https://youtu.be/ktc2AhVU4pQ?list=PLL8pCbx5gnDYUM084cxFpmidjGJJ1bOwf*
- Project Website URL: *https://develop.larc.nasa.gov/2016/summer/ChacoCanyonCross.html*

Drought and Water Resource Management

Drought is a common concern to many park mangers in the western U.S. A changing climate increases uncertainties in how vegetation will respond to changing environmental conditions, including their vulnerability to drought and a warming environment. Participants from the *Western U.S. Water Resources* project partnered with the NPS Northern Colorado Plateau and Greater Yellowstone Inventory and Monitoring Networks to examine shifts in vegetation productivity by examining various environmental variables including precipitation, temperature, evapotranspiration, and water deficit in comparison to a normalized difference vegetation index (NDVI) across a 15-year period. Participants used the *climate pivot point framework* technique (as described below) to assess the ability of vegetation to resist drought when experiencing dry conditions in Utah's Capitol Reef National Park. Climate pivot points can be used as early warning signs of when plant communities may be approaching a point of irreversible change, leading to the transition from one ecosystem to another. The progression to either increased or reduced plant mass in response to climatic variables are identified as climate pivot points, which are symptomatic of drought tolerance in various plant species. Climate pivot points are defined by related environmental indicators of drought such as actual evapotranspiration, precipitation, and temperature. Results from the project provided park managers with information about various vegetation types and which types are most vulnerable to changes in climate and drought. Further, the framework can be reproduced by land managers making critical decisions for other areas.

For more information on this project, see *Drought and Water Resource Management Project* below.

Drought and Water Resource Management Project

Western U.S. Water Resources: Utilizing NASA Earth Observations to Analyze Vegetation Productivity Shifts Relative to Climate Change and Drought in Capitol Reef National Park

- Video URL: *https://youtu.be/2VAbF1z1pO0?list=PLL8pCbx5gnDYUM084cxFpmidjGJJ1bOwf*
- Project Website URL: *https://develop.larc.nasa.gov/2016/summer/WesternUSWater.html*

Air-Quality Monitoring

Air quality and visibility are additional areas of concern for the NPS, including monitoring ozone (O_3), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2) levels within the park system. Unfortunately, there are not enough NPS ground-level air quality monitoring stations to monitor the entire Appalachian Trail. Participants in the *Appalachian Health & Air Quality* project explored how data from the Ozone Monitoring Instrument (OMI) and the Microwave Limb Sounder (MLS) on Aura could be used in conjunction with the NPS's ground-based air-quality observations. The DEVELOP team partnered with individuals from several branches of the NPS including Shenandoah National Park, Harpers Ferry National Historical Park, Great Smoky Mountains National Park, the NPS Air Resources Division, the NPS Northeast Region, the NPS Northeast Temperate Inventory and Monitoring Network, and the Appalachian National Scenic Trail. The team created hotspot maps of the Appalachian Trail and associated national parks, identifying levels of tropospheric O_3, NO_2, and SO_2, to aid park managers in identifying areas with the highest concentrations—see **Figure 5**. The

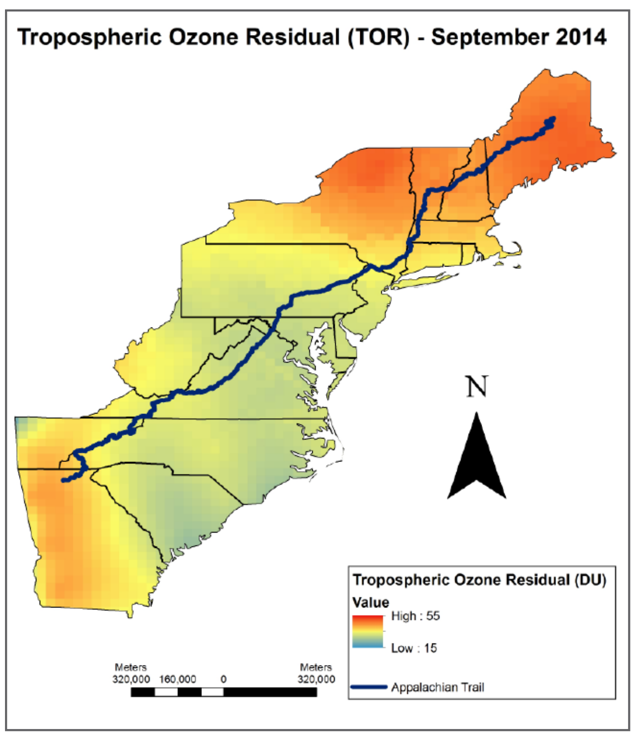

Figure 5. *Appalachian Health & Air Quality.* This feasibility map illustrates the tropospheric ozone residual (TOR) for the Appalachian Trail in 2014 derived using data from OMI and MLS. TOR, inferred through subtraction of stratospheric ozone distribution from total column ozone measurements, indicates the amount of ozone in the troposphere, high levels of which may affect both human health and plant life if experienced for long periods of time. The map shows variations in TOR across the region, and provides the groundwork for further research into this topic by land managers. Understanding TOR is important for land managers, as the Trail spans 14 states and extends for 2189 mi (~3520 km) from Georgia to Maine, receiving approximately 2 million visitors each year. **Image credit:** NASA

maps are particularly useful for areas where there are no ground-level monitoring stations. Overall, the project illustrated how NASA's Earth observation data can supplement NPS's air-monitoring station data to improve air-quality monitoring.

For more information on this project, see *Air-Quality Monitoring Project* below.

Air-Quality Management Project

Appalachian Trail Health & Air Quality: Monitoring Ozone and Atmospheric Pollutants in the Troposphere to Help Regulate Point Source Emissions and to Improve Ozone Advisory Messages by the National Park Service

- Video URL: *https://youtu.be/aHRslRd9gvg?list=PLL8pCbx5gnDYUM084cxFpmidjGJJ1bOwf*
- Project Website URL: *https://develop.larc.nasa.gov/2016/summer/AppalachianTrailHealthAQ.html*

Looking Ahead

The nine DEVELOP projects conducted over the summer built a strong foundation for future collaborations between the NPS and DEVELOP. "This was my first time working with a team from the NASA DEVELOP Program, and it was more than productive; it was rewarding," said **Jalyn Cummings** [NPS, Shenandoah National Park—*Program Manager*]. She continued, "The team generated an idea, formulated a plan, and produced defendable results with very little assistance from me. However, what impressed me the most was the team's ability to explore other research questions I had while simultaneously concentrating on the task at hand. It was truly a rewarding experience." The success of these projects was possible from the strength of the partnerships and engagement between the NPS and DEVELOP.

In April 2017 the NPS and NASA DEVELOP will co-chair a session at the 10th George Wright Society Conference in Norfolk, VA, titled *U.S. National Park Service and National Aeronautics and Space Administration: A Collaborative Effort to Address Park Resource Concerns through Application of Geospatial Imagery*. This session will share the collaborative projects with the broader natural- and cultural-resource-management community to foster future opportunities to integrate Earth observations into resource management.

DEVELOP continues to collaborate with the NPS, and is conducting eight new NPS projects during its Fall 2016 term... More projects are planned for the 2017 spring and summer terms.

"As our Centennial was approaching, the NPS released a document called, *A Call to Action*, that provides guidance for the National Park Service and partners to advance the mission of the NPS into the next 100 years," said **Don Weeks** [NPS, Intermountain Regional Office—*Physical Resources Program Manager*]. Weeks added that, "Our partnership with NASA is strongly aligned to the themes presented in this document, including: sponsoring excellence in science and scholarship, gaining knowledge about park resources, and promoting large landscape conservation to support healthy ecosystems and cultural resources. As the NPS moves into uncertain and dynamic futures, the need to actively track how natural and cultural resources are responding to a range of stressors, including climate change, will continue. The Earth observations and assessments from NASA help to inform that understanding and ultimately guide our decisions grounded on credible science. I see our partnership with NASA essential as we move into the next 100 years."

DEVELOP continues to collaborate with the NPS, and has conducted eight new NPS projects during its Fall 2016 term, broadening the scope of its research interests to include topics related to snow cover, glaciers, and invasive species, as well as expanding to new parks such as the Grand Canyon National Park, Glacier National Park, and the Saguaro National Park. More projects are planned for the 2017 spring and summer terms.

continued on page 57

Enabling Real-Time Earth Observations for Societal Benefits: The NASA Direct Readout Conference 2016

Patrick Coronado, NASA's Goddard Space Flight Center, patrick.l.coronado@nasa.gov,
Kelvin Brentzel, NASA's Goddard Space Flight Center, kelvin.w.brentzel@nasa.gov
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Introduction

Direct Readout (DR) is the process of acquiring freely transmitted live remote sensing satellite data. Direct Broadcast (DB) refers to the real-time transmission of remote sensing satellite data to the ground. DR has tremendous utility in times of disaster; for example, when Hurricane Matthew raced toward Haiti and then headed for the U.S. mainland in October 2016, real-time (RT) imagery of the storm track—made possible by DR from NASA-developed satellites—provided disaster managers at the Federal Emergency Management Agency (FEMA) with a powerful response tool. This article will begin with an overview of the evolution of DR and DB capabilities generally, then describes NASA's Direct Readout Laboratory (DRL), which serves as a bridge between the needs of the global DR user community and NASA mission objectives to join end-user applications to NASA's science activities. After establishing that background, it will then summarize the ninth NASA Direct Readout Conference (NDRC-9) that took place June 21-24, 2016 in Valladolid, Spain.

What is Direct Readout?

Disaster management is just one example of many RT applications that DR and DB enables. These capabilities are not limited to governmental agencies; the *DR user community* also includes academic and commercial users. Users with compatible ground receiving equipment and in direct line of sight to a satellite may receive DB data, and there are now over 220 receiving sites worldwide. These sites use NASA-developed technologies, and 85% of them support real-time applications. And in fact, a receiving station is no longer necessary to acquire DB data; they are now freely available from the Direct Readout Laboratory (DRL) at NASA's Goddard Space Flight Center (GSFC), which will be described further in this article, and from numerous other receiving sites, or from global archives such as NASA's Land, Atmosphere Near Real-time Capability for the Earth Observing System (LANCE)[1] or the National Oceanic and Atmospheric Administration (NOAA)'s Comprehensive Large Array-data Stewardship System (CLASS)[2]. The technologies necessary to process the data are freely available from the DRL, meaning that anybody, anywhere in the world, may be enabled by NASA's science activities for their own applications and—as a result—DR technologies foster global data exchange and scientific collaboration. Live, local, and regional environmental data, in turn, benefit environmental, commercial, and public-interest decision-making.

Evolution of Direct Readout[3]

DB capabilities date back to nearly the beginning of the space age. They were designed into NOAA's Television Infrared Observation Satellites (TIROS) beginning in 1962. Prior to TIROS, normal satellite operations involved recording instrument measurements on an onboard tape recorder that was later dumped to a dedicated ground receiving station for processing. Users and managers soon realized that the satellites themselves would make excellent distribution vehicles, and thus the concepts of DB and DR were developed.

During this early stage of what would come to be known as satellite remote sensing, scientists and application engineers realized that the varied ways electromagnetic radiation interacts with matter could provide quantitative measurements of the parameters of interest to various Earth science disciplines. An important technology breakthrough occurred with the Nimbus series of experimental weather satellites, where many new and innovative suites of instruments allowed experimenters to explore the use of the entire spectrum to monitor and measure a significant range of phenomena not only of atmospheric interest, but also to scientific explorers of the ocean, land, and Earth's vegetation.[4]

In 1972 the first High Resolution Picture Transmission (HRPT) system was developed at GSFC. HRPT enabled data from the Very High Resolution Radiometer (VHRR) and Vertical Temperature Profiling Radiometer (VTPR) to be sent directly to DR ground-receiving stations, the costs of which were significantly reduced with the advent of Microvax computers. At this time, the cost of a ground receiving station was still high (~$1 to $1.5M), but the expectation of a long continuous series of satellites producing significant datasets with multiple applications led large organizations and institutions to invest in the technologies.

In 1983 GSFC and NOAA joined forces to develop a complete satellite ground system based entirely on the use of DR data from the Improved TIROS Operational

[1] For more information on LANCE, visit *https://earthdata.nasa.gov/lance*.

[2] For more information on CLASS, visit *http://www.class.ngdc.noaa.gov.*

[3] For more detailed historical perspective, refer to Coronado, P. and K. Brentzel, "NASA Direct Readout for Its Polar Orbiting Satellites" in *Earth Science Satellite Remote Sensing, Vol. 2—https://directreadout.sci.gsfc.nasa.gov/links/rsd_eosdb/PDF/NASA_DR_Polar_Orbiting_Satellites.pdf.*

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

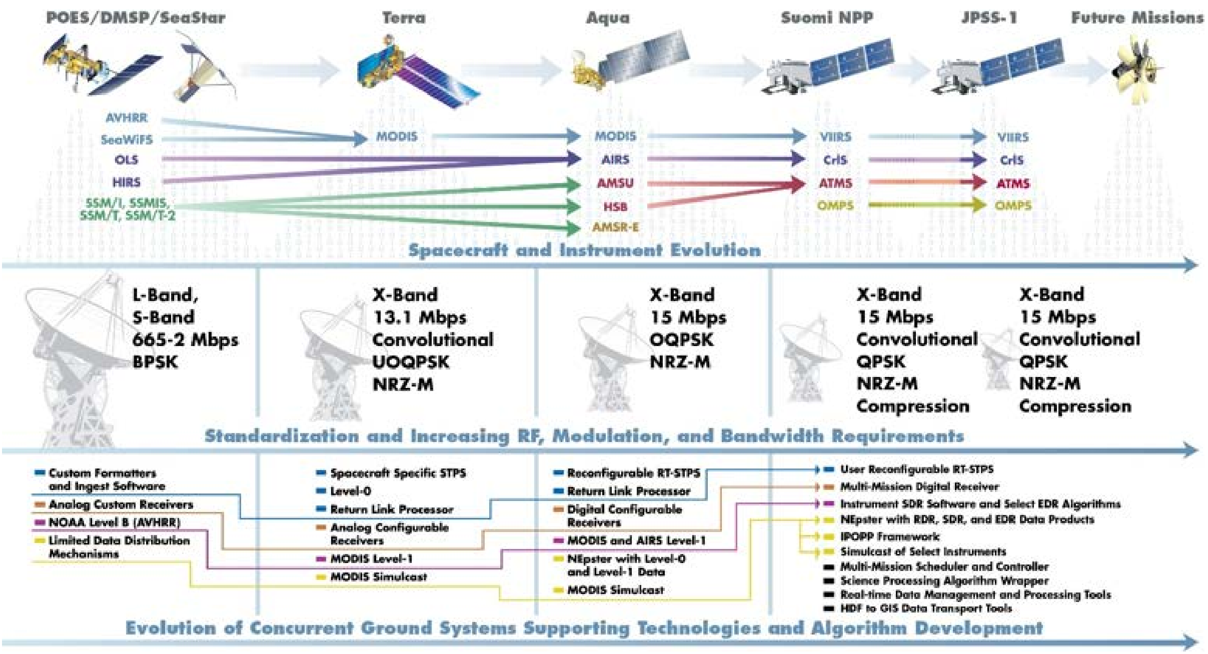

Figure 1. Shown here is a *Direct Readout Technology Roadmap* that depicts the evolution of DR technologies from the POES through JPSS Missions. Note the shift to X-band DB transmission beginning with Terra. **Image credit**: NASA's DRL

System (ITOS). By 1989, GSFC had made significant improvements to the hardware and software of DR systems such that data from polar-orbiting satellites [e.g., TIROS, U.S. Department of Defense's Defense Meteorological Satellite Program (DMSP)], as well as data from geosynchronous satellites [e.g., NOAA's Geostationary Operational Environmental Satellites (GOES) and Japan Aerospace Exploration Agency's (JAXA) Geostationary Meteorological Satellites (GMS)], could be received, processed, and analyzed in near-real time (NRT) in an automated fashion. An added benefit from the integration of the DMSP satellites was that they used unique microwave instruments based on the Nimbus instruments;[5] in the late 1980s to early 1990s the data products from DMSP satellites were made available to the research community. These products would eventually influence the design of the future Joint Polar Satellite System (JPSS), which will also take advantage of DR and DB capabilities, as will be discussed later in this article.

Terra was the first mission to feature an X-band, DB transmission—and in that sense it was a pathfinder mission for DB.

The Direct Readout Laboratory

The NASA DRL originated in 1996 and began working closely with DB missions to provide a DR *technology roadmap* (see **Figure 1**) that ensures continuity, cohesiveness, and standardization to minimize end-user impacts and promote collaborations.

NASA's DR Conduit

The very first DB transmission from the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard NASA's Terra spacecraft was received at the DRL in January 2000—not long after the mission was launched in December 1999. Initially NASA envisioned DB/DR as a risk-reduction mode in case of disruption to the baseline Stored Mission Data (SMD) flow, but NASA and NOAA together soon recognized that this capability promised far greater utility for both agencies as well as the broader user community. As shown in Figure 1, Terra was the first mission to feature an *X-band*, DB transmission—and in that sense it was a pathfinder mission for DB. Prior to that, all DB transmissions were in the *L-band* region.[6] X-band provides higher spectral/spatial resolution, and X-band receiving stations would prove less costly for users.

The first big challenge for acceptance of X-band by the DR community [i.e., L-band users on the legacy Polar-orbiting Environmental Satellites (POES)] who would benefit from the Terra's higher spectral/spatial resolution over heritage instruments was in the cost and complexity of the antenna tracking, ground

[5] The special sensor microwave/imager (SSM/I) is a seven-channel, four-frequency, linearly polarized passive microwave radiometer system. Its predecessor, the Scanning Multichannel Microwave Radiometer (SMMR), which flew on Nimbus-7 and SeaSat, provided similar information. Its successor, the Special Sensor Microwave Imager/Sounder (SSMIS), is an enhanced eleven-channel, eight-frequency system that also flies on DMSP satellites.

[6] The microwave portion of the electromagnetic spectrum is broken down into a series of 14 bands: The L-band covers frequencies from 1 to 2 GHz (15 to 30 cm wavelength); the X-band covers frequencies from 8 to 12 GHz (25 mm to 37.5 mm). A complete list is available at *https://en.wikipedia.org/wiki/Microwave.*

systems, and signal processing. The DRL collaborated with the commercial sector to develop a new cost basis for X-band DB acquisition, resulting in an order of magnitude cost reduction for receiving stations—from ~$1.5 million to $150,000—over a period of several years spanning the Terra and Aqua eras. During this time the DRL also defined a generalized template that the commercial sector adopted to create their own value-added DB acquisition capability; this set a precedent, and since then the DRL has supplied emerging technologies, algorithms, ancillary/auxiliary data, and documentation to the user community. The availability of inexpensive X-band receiving stations and applicable free technologies combined to dramatically increase the use of DR, worldwide.

Planners and users of data from the Aqua mission (launched in May 2002) requested increased involvement from the DRL in ascertaining user needs and means to mitigate possible impacts. As a result, the role of the DRL as the intermediary between NASA Earth-science missions and the user community was now firmly established,[7] and DRL technologies adopted by the commercial sector and end-users became the basis for the Earth Observing System (EOS) DR capability.

DRL's involvement with remote sensing missions expanded with the development of the Suomi National Polar-orbiting Partnership (NPP)[8]—launched in 2011. NPP pre-phase A Team engaged DRL to contribute to the outreach element of the mission. DRL was involved in all aspects of communication and instrument payload trade studies and also participated in all engineering opportunities and NPP Compatibility Tests. This approach also served as a risk-reduction measure for the software that would later be provided through NASA's Software Public Release. Once again, the DRL developed the template for DR acquisition, and was the first organization to produce Level-2 [Environmental Data Records (EDRs)] from the DB downlink following the October 2011 launch and subsequent DB service-commissioning phase. Based on the success of DRL's EOS model, NOAA funded the laboratory to develop their DR template, which will contribute significantly to the success of future NOAA missions.

Looking ahead to the JPSS era, DRL has continued consultation in developing mission documentation for JPSS-1, provided preprocessing software to the flight team for acquisition and RT data dissemination to each instrument team, and has begun porting science algorithms for DR RT applications. DRL will again perform downlink monitoring and characterization during the commissioning phase, and the DRL will continue to provide the user community with ancillary and auxiliary data, relevant mission documentation, and designated science algorithms. The greater than 3000 registered users will surely appreciate access to such tools and documentation.

Connecting NASA Science to Applications

The DRL provides all of the technologies necessary for users to preprocess, process, visualize, and analyze DB data in a multisatellite, multimission environment. The DRL works closely with principal investigators from NASA science teams to validate, iterate, and improve Science Processing Algorithms (SPAs) for RT applications to provide the highest-quality science while minimizing latency in receipt of the data after instrument acquisition. As a matter of policy, the decision to make algorithms available to the public requires coordination between NASA Science Teams (research), LANCE (NRT global product access), and the DRL (RT product access and software public release). NASA science leadership must corroborate all DRL algorithm implementation.

Upon request, the DRL supplies RT imagery to LANCE for use by decision-makers on behalf of the NASA Disasters Program, including the FEMA, the U.S. Geological Survey (USGS), and the NASA Short-term Prediction Research and Transition Center (SPoRT). See **Figures 2** and **3** for recent examples of such applications.

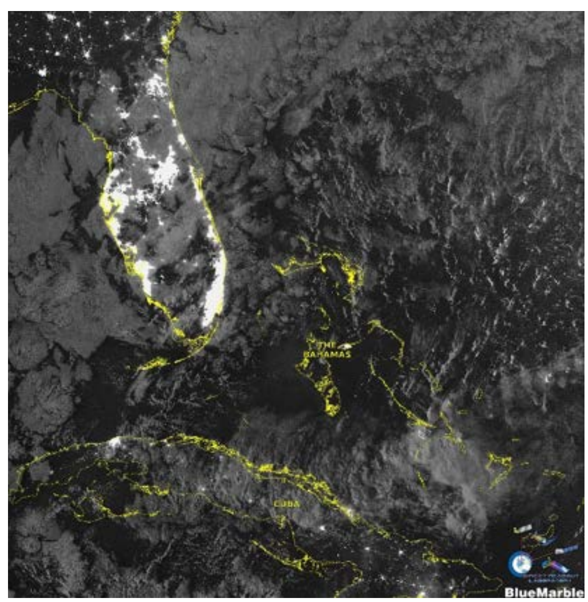

Figure 2. On October 4, 2016, Hurricane Matthew made landfall in Haiti. This is the last in a series of images the DRL produced as it tracked the hurricane before, during, and after it made landfall beginning with the island of Haiti. The night image shown here is an Enhanced Near Constant Contrast (ENCC) image produced using BlueMarble 1.6a and SectorView 1.2a (see **Vanu Dasgupta's** presentation summary on page 27 of this article for description) to process data from the Visible Infrared Imaging Radiometer Suite (VIIRS) on Suomi NPP. ENCC imagery is used to determine power outages in order to map impact zones. **Image credit:** NASA's DRL

[7] NASA's Aura mission, launched in 2004, also features a DB capability, however, it is limited to the Ozone Monitoring Instrument (OMI), transmitting data to the Finnish Meteorological Institute (FMI).

[8] At launch, Suomi NPP was named the National Polar-orbiting Environmental Satellite System (NPOESS) Preparatory Project, also known as NPP. Appropriate use of NPP depends on the timeframe under discussion.

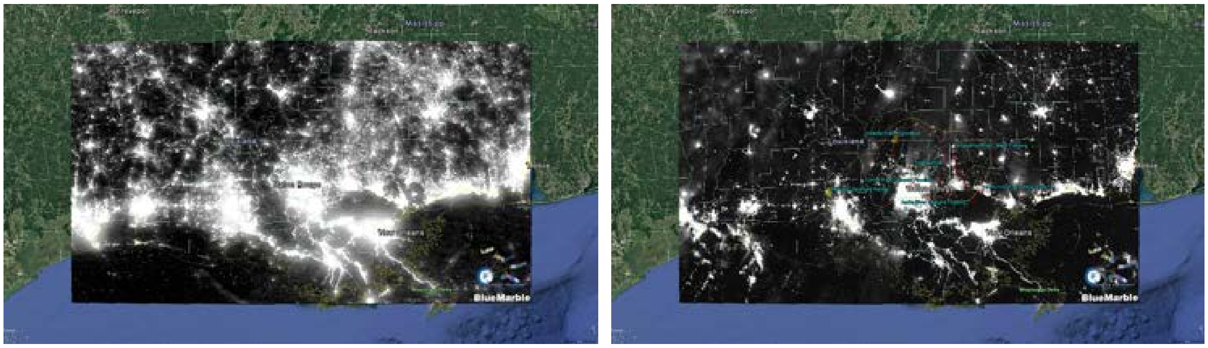

Figure 3. On August 15, 2016, areas of Louisiana received extremely heavy rainfall as a result of a nontropical low that slowly meandered over the area. The images show Louisiana at night on May 7, before the flood [*left*] and on August 15, after the flood [*right*]. These ENCC images were produced by the DRL using BlueMarble 1.6a and SectorView 1.2a (see **Vanu Dasgupta's** presentation summary on page 27 of this article for description) to process data from VIIRS on Suomi NPP. These images were featured in the *New York Times* and can be viewed at *http://nytimes.com/interactive/2016/08/22/us/louisiana-flooding-maps.html?_r=2* **Image credit:** NASA's DRL

The Ninth NASA Direct Readout Conference

The University of Valladolid Remote Sensing Laboratory hosted NDRC-9, which attracted 190 participants representing 35 countries. Conference sponsors included the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT); World Meteorological Organization (WMO); U.S. Department of Agriculture (USDA)'s Forest Service (FS) Remote Sensing Applications Center (RSAC); Oregon State University; and University of Wisconsin (U-W) Space Science Engineering Center (SSEC).

Vendor Presentations

Close collaboration with vendors has been key to the evolution and acceptance of DR. This community has provided keen insights into algorithm and system implementation in operational systems, as well as commercial availability of such capabilities. The conference addressed a variety of commercial and applications themes summarized in the **Table** below.

Table. Material covered during vendor presentations at NDRC-9.

Applications for Societal Benefits of Direct Readout
• *Agriculture:* Supporting sustainable agriculture and combating desertification. • *Disasters:* Synoptic, low-latency observations that are critical to support disaster mitigation and response activities, thereby reducing loss of life and property from natural and human-induced disasters. • *Ecosystems:* Improving the management and protection of terrestrial, coastal, and marine resources. • *Weather:* Improving access to RT weather information, forecasting, and warning.
Science and Algorithms for Direct Readout
• Algorithm calibration • Regional/global product validation • Continuity from EOS to Suomi NPP and beyond • Nowcasting and forecasting modeling using RT data
DR Technology Tools, Measurement and Data Processing Techniques
• Efficient image processing, scaling, and smoothing techniques • Real-time data visualization tools • Data dissemination via geostationary communication systems • NRT science data processing systems • Operational and research processing software packages for DR applications

Plenary and Poster Sessions Overview

During the workshop's plenary and poster sessions, participants were asked to consider:

- What kinds of applications are you interested in seeing developed?
- What types of data and algorithms are needed for your potential and/or existing application and information needs?
- What are the actual or potential uses of the presented algorithms/product/application in the context of your organization's needs?
- Are there particular challenges/shortcomings/ unmet needs? Where can things be made better?
- Are there opportunities for collaboration with other attendees and workshop leads (e.g., regional applications and data sharing)?
- What scenarios can you discuss with the broader group to identify innovative ideas and potential improvements?

Each day of the conference agenda focused on a particular discipline:

Day 1—*Crosscutting Science and Technology*, Chair: **Patrick Coronado** [GSFC, DRL—*Head of the Direct Readout Laboratory*];

Day 2—*Real-Time Land Science Applications*, Chair: **Brad Quayle** [USDA FS RSAC—*Chair of the International Land Direct Readout Coordinating Committee*];

Day 3—*Real-Time Oceans/Fresh Water Remote Sensing*, Chair: **Jasmine Nahorniak** [OSU—*Chair of the International Direct Readout Ocean Steering Committee (IDROSC)*]; and

Day 4—*Real-Time Atmosphere Science Applications*, Chairs: **Anders Soerensen** [EUMETSAT] and **Allen Huang** [U-W/SSEC] both from theInternational TOVS[9] Working Group (ITWG).

Given the sheer number of presentations and the depth of technical detail, the summary report that follows provides only a representative overview of the meeting. Complete presentation, workshop, and poster files are available at *http://directreadout.sci.gsfc.nasa.gov/?id=dspContent&cid=244*.

Day One: Crosscutting Science and Technology

Patrick Coronado opened the NDRC-9 and reviewed objectives, emphasizing the need to better understand the role that DR plays in decision-support systems, and identifying areas that would improve the decision-making process. He expressed his hope that the NDRC-9 would foster community cohesion around issues including standardization of data and product formats.

Manuel Lopez [University of Valladolid] and **José-Luis Casanova** [Laboratory of the University of Valladolid (LATUV), Spain] welcomed participants to Valladolid. Casanova summarized the evolution of DR implementation at LATUV from 1991 to the present. Applications for DR at LATUV include monitoring fisheries, crop forecasting, insurance applications, forest monitoring, weather forecasting, and flood monitoring. They noted that LATUV maintains an extensive archive of daily satellite images.

Eduardo de Miguel Lanes [National Institute of Aerospace Technology (INTA), Spain] highlighted INTA NRT applications, including airborne remote sensing with hyperspectral imagers (e.g., Airborne Hyperspectral Scanner and Compact Airborne Spectrographic Imager), and participation in the EUMETSAT Advanced Retransmission Service (EARS) to enable short-range regional weather-prediction models.

Coronado presented EOS and Suomi NPP/JPSS-1 mission and instrument updates on behalf of **David Green** [NASA Headquarters (HQ)]. He noted that while all of the EOS flagship missions (Terra, Aqua, and Aura) are aging, they continue to provide excellent science data. These missions are projected to last for at least another six to nine years. The Suomi NPP VIIRS on-orbit performance has become stable after four-and-a-half years in orbit. Multiple and major instrument calibration activities in the coming year will be more challenging for both the MODIS Calibration Support Team and the VIIRS Calibration Support Team.

Tsengdar Lee [NASA HQ] presented the NASA science roadmap for the Earth Science Division, including an on-orbit constellation overview; a review of upcoming launches and mission development; Venture Class[10] status, plans, and schedule; and plans for sustained land imaging. Highlights included In-Space Validation of Earth Science Technologies (InVEST), an on-orbit technology validation and risk reduction program for small instruments and instrument systems that could not otherwise be fully tested on the ground or airborne systems.

Coronado stated that the DRL, acting as the implementation arm of the NASA Direct Readout Program, has been bridging the gap between NASA science and end-user applications, thereby developing support technologies and porting science algorithms to function in a multisatellite, multiinstrument DR environment for applications users. DRL technologies include real-time system processing tools, packet reassembly and standard

[9] TOVS stands for Television Infrared Observational Satellite (TIROS) Operational Vertical Sounder

[10] To learn more about Venture Class missions, visit *https://essp.larc.nasa.gov*.

data reformatting tools, instrument-specific calibration and georegistration algorithms; an SPA wrapping schema for standard system integration and sustainment; and real-time data distribution mechanisms, such as Simulcast.

Miguel Román [GSFC] reported on the role of NRT/DR at NASA in disaster-response activities. The NASA Applied Sciences Disasters Program promotes the use of Earth observations to improve the prediction of, preparation for, response to, and recovery from natural and technology caused disasters. The Disasters team and network of partners and volunteers assist with assessing hazards, evaluating severity, and identifying impacts near vulnerable infrastructure, crops, and lifelines, and—especially in remote areas where observations are sparse—providing guidance for action.

Diane Davies [GSFC] reported that LANCE supports application users interested in monitoring a wide variety of natural and manmade phenomena. Global NRT data and imagery from many instruments, including MODIS and VIIRS, are available from LANCE much more quickly than routine processing allows. Specifically, most LANCE-based data products are available within three hours from satellite observation; NRT imagery is generally available three to five hours after observation.

Fred Patt [GSFC] reviewed the status of VIIRS Level-1 software. He stated that NASA VIIRS Level-1 Algorithm/Software Working Group (L1ASWG) was formed to develop software and data product formats to support NASA's climate data research requirements. The first release of the software was completed in October 2015 and is operational at all three VIIRS Science Investigator-led Processing Systems (SIPS). He explained that the software has a number of features that also support DR data processing, and public release of the software is planned.

Seppo Hassinen [Finnish Meteorological Institute (FMI)] discussed volcanic detection and air-quality monitoring using the Ozone Monitoring Instrument (OMI) on Aura and Ozone Mapping Profiler Suite (OMPS) on Suomi NPP (and planned for JPSS). Hassinen focused on monitoring volcanic emissions of ash and sulfur dioxide from the perspective of aviation security, and provided a scenario describing air-quality monitoring.

Thomas August [EUMETSAT] reviewed the status of operational hyperspectral Level-2 products, from global to regional services. He explained that the Infrared Atmospheric Sounding Interferometer (IASI) Level-2 processing chain provides essential geophysical parameters, which are distributed in NRT to users via EUMETCast and the Global Telecommunications System. The high quality and yield of the IASI Level-2 Version 6 products is showing potential for different applications and in particular for regional applications (e.g., nowcasting), where timeliness is critical.

Vanu Dasgupta [GSFC] announced the release of the DRL's *BlueMarble SPA v1.5*, an evolving tool that bridges the gap between science data products and end-user applications.[11] He explained that the potential of regionally produced NRT EOS and Suomi NPP science data products is often not fully realized from the standard research data products. This is due to a lack of available tools that can unlock the unique features that may be derived from these standard products. It empowers end users by giving them an easy to use tool to unlock these unique features, thereby enhancing their user experience as well as extending the utility of their decision-support systems. Within the design of BlueMarble there is special attention given to ease of use and utility of value-added products. BlueMarble features a combination of core utilities. Dasgupta presented examples of extended application-specific multimission and multisensor data products that BlueMarble produces, including comparisons of images before and after BlueMarble sharpening had been applied.

Day Two: Real-Time Land Science Applications

Brad Quayle welcomed participants to the Land session, reviewed the day's agenda, and provided a brief overview of how USDA's FS RSAC uses NRT data to support critical applications, including wildfire detection, monitoring, and characterization in the U.S. and Canada, and forest health monitoring in the U.S. RSAC uses EOS MODIS and Suomi NPP VIIRS data operationally, and is part of a DR data-sharing network with partner ground stations.

Alexei Lyapustin [GSFC] led the *Multi-angle Implementation of Atmospheric Correction (MAIAC) Algorithm Workshop*. MAIAC is a new algorithm that uses time-series analysis and processing of pixel groups for advanced cloud detection and retrieval of aerosol and surface bidirectional reflectance properties. Recent studies showed that MAIAC significantly improves the accuracy of atmospheric correction for northern latitudes and tropics—including the Amazon region—as compared to standard MODIS surface reflectance products. Lyapustin provided an overview of MAIAC processing and products with several application examples.

Vanessa Escobar [GSFC] led the *Soil Moisture Active Passive (SMAP) Mission Workshop*, covering mission status, post launch applications, and the use of data products by Early Adopters and the SMAP user community. Now in Phase E of the mission's life, SMAP plans to gather lessons learned from its community and get a better

[11] BlueMarble creates VIIRS and MODIS sharpened True Color imagery as well as VIIRS and MODIS Natural Color imagery; VIIRS Enhanced Near Constant Contrast (ENCC) day and night imagery; and overlays of OMPS sulfur dioxide and OMPS Aerosol on VIIRS Sharpened True Color. To learn more about BlueMarble and to read about the latest features, visit *https://directreadout.sci.gsfc.nasa.gov/?id=highlights_archive#242*.

understanding of the mission's impact in areas of applications. Early Adopter case studies are being conducted in weather, agriculture, flood, drought, health, and national security to help quantify the value of SMAP data.

Francisco Tapiador [University of Castilla-La Mancha (UCLM), Spain] led the *Applications of Real-time Satellite Precipitation Estimates Workshop*. The Global Precipitation Measurement (GPM) mission constellation provides products that are suitable for the NRT monitoring of extreme hydrometeorological events. Tapiador reviewed the applicability of the GPM precipitation estimates in the land research realm.

Wilfrid Schroeder [GSFC] led the *Active Fires Workshop* and covered the latest MODIS Collection 6 and VIIRS active fire algorithms. Schroeder described the MODIS Collection 6 algorithm changes that targeted outstanding commission and omission errors, highlighting improved fire detection performance metrics relative to the Collection 5 algorithm. Schroeder demonstrated two of the VIIRS active fire products: the baseline 750 m (~2461 ft) resolution dataset using an adapted MODIS Collection 6 algorithm; and the new 375 m (~1230 ft) product providing higher-resolution fire-detection data. The workshop also described select regional and global fire mapping and emissions and air-quality applications that serve the broader user community.

Louis Giglio [GSFC] led the *Burned Area Mapping and Monitoring Algorithms Workshop*. This workshop covered the status of the Collection-6 MODIS burned area product, and progress in adapting the mapping approach to the VIIRS instrument. Giglio also described a potential path for developing a true, NRT burned-area mapping algorithm, optimized for DB applications.

Philip Frost [Council for Scientific and Industrial Research (CSIR), South Africa] led the *Advanced Fire Information System (AFIS) Workshop*. AFIS is a web-based and mobile application for mapping, visualizing, and monitoring global active fires, as well as burned areas in NRT from satellite- and ground-based sensors. Fire danger and weather forecast model output integration and fusion facilitate decision support, as does crowdsourcing through an innovative mobile app linked to an online dashboard.

Dan Slayback [GSFC] led the *Monitoring Flood Events with NASA's NRT Flood Mapping Products Workshop*. GSFC's Global Flood Mapping project generates NRT flood and surface water maps from the MODIS and Landsat instruments.[12] These products are freely available, and are also often incorporated into maps customized for the specific event by the Dartmouth Flood Observatory. Slayback described the strengths and limitations of these products, along with the ability to examine the product archive to place current events in context.

[12] Landsat does not have a DB capability; NRT Landsat data are acquired via the globally targeted downlink/dump.

Dath Mita [USDA] led the *USDA World Agricultural/Food Security Workshop*. Mita discussed the USDA's Foreign Agricultural Service (FAS) demonstration of the joint USDA–NASA Global Agricultural Monitoring (GLAM) website (*http://glam1.gsfc.nasa.gov*), whereby 250-m (~820-ft) resolution MODIS time series imagery is used operationally to estimate relative crop yields, worldwide. In addition, Mita discussed operational processing of Landsat-7 and Landsat-8 imagery for estimating national crop area and crop type at 30-m (~98-ft) resolution.

Day Three: Real-Time Oceans/Fresh Water Remote Sensing

Jasmine Nahorniak welcomed participants to the Oceans/Freshwater session, reviewed the day's agenda, and provided a brief overview of DR utilization at OSU. Nahorniak chairs the IDROSC, which acts as a conduit between the ocean DR community and relevant agencies. In addition to providing a voice for this community, the IDROSC also provides access to information about ocean-specific satellite sensors and software on its website (*IDROSC@coas.oregonstate.edu*).

Ichio Asanuma [Tokyo University of Information Sciences (TUIS), Japan] discussed the use of the VIIRS Day/Night Band (DNB) to detect fishing activities. Light distributions detected by DNB were studied with vessel locations provided by the Automatic Identification System (AIS), which reports the locations of vessels greater than 300 tons, and the lights from fishing boats. Asanuma discussed using brightness temperature measurements from band M12 as a threshold to distinguish the lights of vessels from the surface background lights, with the moon and illuminated clouds present.

Miguel Román [GSFC] led the *Suomi NPP VIIRS Nighttime Environmental Products for Land Science and Disaster Response Applications Workshop*. A pioneering new generation of satellite instruments, based on the success of the VIIRS DNB, now offers global measurements of nocturnal visible and near-infrared light that are suitable for Earth science and climate studies. These novel low-light measurements open doors to a wealth of new and expanded interdisciplinary research topics, including urban sustainability, improved weather forecasting, and enhanced climate data records. Román covered the following core applications areas: fundamental questions and challenges in quantitative nighttime remote sensing; novel capabilities, applications, and algorithms involving VIIRS DNB measurements of interest to the research and operational communities; and temporal studies of night light to detect changes in brightness. (Figures 2 and 3 show examples of the VIIRS DNB data being used to monitor disasters.)

Susanne Mecklenburg [ESA] provided an overview and current status update of the Copernicus Sentinel-3 Mission. Optical imaging payloads on the Sentinel-3A and -3B missions include the Ocean and Land Color

Instrument and the Sea and Land Surface Temperature Radiometer used to assess ocean color and land surface/vegetation conditions. The topography mission payload consists of the Synthetic Aperture Radar Altimeter and the MicroWave Radiometer, used to support the measurement of sea surface and land ice topography. NRT Level-2 ocean, land, and atmosphere data products from Sentinel-3 will be available from ESA less than three hours after acquisition.

Fred Patt led the *SeaWiFS Data Analysis System 7 (SeaDAS) for Ocean Data Users Workshop*. He described the features and functionalities of SeaDAS, which is a comprehensive image-analysis package used to process, display, analyze, and implement quality control for ocean color data. While originally developed to support the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) mission, it now supports most U.S. and international ocean color missions. The primary focus of SeaDAS is ocean color data, but it is applicable to many satellite-based Earth science data analyses. SeaDAS System 7 represents the most significant overhaul of SeaDAS in decades.

Cara Wilson [NOAA's National Marine Fisheries Service (NMFS)/Southwest Fisheries Science Center (SWFSC) Environmental Research Division] led the *Fisheries Workshop*. As a field of study, "fisheries" encompasses not just commercially important fish stocks, but all living marine resources (LRMs), including threatened and endangered species of fish, as well as marine mammals and invertebrates. Wilson covered the three distinct aspects of fisheries—harvesting, assessment, and conservation—and discussed how NRT satellite data are used in these applications.

Menghua Wang [NOAA's Satellite and Information Service (NESDIS)/Center for Satellite Applications and Research (STAR)] discussed VIIRS ocean-color products from the global open ocean and coastal and inland turbid waters. VIIRS ocean-color products derived from the NOAA Multi-Sensor Level-1 to Level-2 (MSL12) ocean-color data-processing system were evaluated and compared with those from *in situ* measurements and ocean-color data derived from Aqua MODIS. Results show that VIIRS is capable of providing high-quality global ocean-color products in support of both scientific research and operational applications.

Erin Urquhart [EPA] led the *Monitoring for Ecosystem and Human Health Workshop*. Urquhart focused on creating an interoperable network for applied and operational use of DR technology in coastal and inland waters. Topics included the potential for mobile application dissemination, oil spill monitoring, detecting inland and coastal harmful algal blooms (HAB), exposure risk applications for municipal drinking and recreational systems, and citizen science. The objectives were to identify existing resources, gaps, and next steps toward building networks to address water quality.

Day Four: Real-Time Atmosphere Science Applications

Anders Soerensen, Allen Huang, and **Carlos Cabanas** [EUMETSAT] presented an overview of Atmosphere NRT activities and applications, including meteorological satellites, instruments, and products.The presentation was divided into sections covering the developments in the U.S., Europe, Russia, and China. Starting from current missions, it provided an outlook for future missions and applications.

Christian Retscher [EUMETSAT] highlighted general aspects of atmospheric composition and provided an overview of related main application areas, the role of satellite-based remote sensing in monitoring and forecasting atmospheric composition, and related measurement techniques. Retscher focused on application areas to monitor stratospheric ozone and air quality, but also discussed aspects of biomass burning, fire emissions, and volcanic eruptions as well as monitoring greenhouse gases. He concluded with a discussion of EUMETSAT missions relevant to atmospheric composition, and provided an outlook on the potential data uses of DR.

Anders Soerensen presented an overview of the EUMETSAT EARS network and the new VIIRS DNB service. The EARS regional data services deliver products from polar orbiting meteorological satellites made available within 15 to 30 minutes after sensing, through the local processing, collection, and redistribution of sounding and imagery data acquired directly from the satellites at a network of DR stations. This short latency, combined with more-frequent observations available from multiple satellites, make products useful for nowcasting and numerical weather prediction (NWP) applications over Europe. Soerensen showed imagery that demonstrated the utility of the VIIRS DNB for distinguishing low clouds and fog from the ground in nighttime imagery.

Carlos Cabanas reviewed the status of the new Feng Yung (FY)-3 based service.[13] In 2015 the Chinese Meteorological Administration (CMA) FY-3C satellite was integrated into EARS, and is now providing a new regional Vertical Atmospheric Sounding Service (EARS-VASS) from data acquired from the early morning polar orbits at the Lannion, France; Athens, Greece; Svalbard Norway; Kangerlussuaq, Greenland; and Maspalomas, Canary Islands stations. EUMETSAT is now establishing sounding and imager services based on DB data provided by the FY-3D satellite, scheduled for launch in November 2016.[14]

Adam Dybbroe [Swedish Meteorological and Hydrological Institute (SMHI)] led the *Nowcasting: Polar Platform System (PPS) Algorithms and Products Workshop*.

[13] FY-3 is the second generation of Chinese polar-orbiting weather satellites; they are a follow-on to the FY-1 series.
[14] **UPDATE**: FY-3D is now scheduled for launch in December 2016.

PPS is a software package that provides algorithms and infrastructure to generate cloud and precipitation products from VIIRS on Suomi NPP (and planned for JPSS) and Advanced Very High Resolution Radiometer[15] data. This workshop familiarized participants with PPS products and how to interpret them, and provided examples of how they can be used in nowcasting. Dybbroe concluded with a demonstration of how PPS can be run in a real-time environment.

William Bell [U.K. Meteorological Office] led the *DB Data in NWP Workshop*. This workshop covered the use of DB data in regional and global NWP, with the use of such data in the U.K. Met Office as an example. Bell summarized the benefits of various data types for global and regional NWP, and demonstrated how the timeliness constraints imposed by regional NWP drive the need for DB data. The workshop considered some of the challenges found in using satellite data in regional NWP.

Allen Huang discussed the transition from EOS to Suomi NPP and the role of U-W software packages including the International MODIS/AIRS Processing Package (IMAPP) and the Community Satellite Processing Package (CSPP). IMAPP continues to support the EOS DR community with Terra MODIS, Aqua MODIS, and Aqua Atmospheric Infrared Sounder products and applications software. CSPP continues to support the polar-orbiting satellite DR community with a wide range of software and products supporting Suomi NPP, MetOp, NOAA, EOS, and FY-3 satellites. CSPP is being prepared for NOAA-20 (JPSS-1) support beginning early in 2017.

Kathy Strabala [U-W/SSEC] led the *IMAPP Training: From Theory to Applications Workshop*. The IMAPP DB training workshops strive to promote the use of Aqua and Terra DB data to enhance environmental forecasting and decision making. The course focuses on the use of locally acquired data and products from organizations that manage X-band antennas around the world. These are hands-on, practical courses focused on teaching environmental decision-making skills based on remote-sensing data. To date, 12 workshops have been taught on 6 continents, attended by students from more than 60 countries.

Martin Raspaud [SMHI] and **David Hoese** [U-W/SSEC] led the *Community Software Tools Workshop*, highlighting the Pytroll and Polar2Grid tools. Raspaud described Pytroll, which comprises almost 20 free and open source Python modules to read, analyze, process, and write weather-satellite data. The workshop began with a presentation on the capabilities of different Pytroll modules, which include cover data reading, combining, remapping, and decorating. After that came some real-world Python code examples of how to perform different weather-satellite-related data processing tasks, using polar-orbiting imager data. Hoese discussed Polar2Grid, an all-in-one precompiled software package that makes it easy to create high-quality images from satellite data files with a simple command-line interface. Since its inception, Polar2Grid has grown into a robust Python package that supports more than seven satellite data formats (including Terra and Aqua MODIS HDF4), and more than four output data formats, while still being usable from a single command-line call.

[15] The first AVHRR was a four-channel radiometer, first carried on TIROS-N (launched October 1978). This was subsequently improved to a five-channel instrument (AVHRR/2) that was initially carried on NOAA-7 (launched June 1981). The latest instrument version is AVHRR/3, with six channels, first carried on NOAA-15 launched in May 1998.

Conclusion

Patrick Coronado concluded the conference by thanking participants, the NDRC-9 organizing committee, the discipline leads and, especially, the University of Valladolid for hosting the conference. The team had several recommendations moving forward, addressing the need to:

- Have a voice to promote the availability of DB capabilities on future missions from NASA, NOAA, and other international space agencies.
- Assess and monitor new and evolving satellite missions for data and products that may be utilized in RT/NRT applications by all relevant scientific disciplines and to support continuity in observations. The community thought it was important to consider ways to integrate social media into decision support systems, as these models are used to monitor hazards, ecosystems, human health, and other relevant topics, which can all benefit from instantaneous feedback mechanisms afforded by social media.
- Foster additional communications activities in the DR community between conference events.
- Promote the success of the VIIRS DNB, which is performing above specification; this should be widely advertised and more attention paid to potential DNB applications.
- Make satellite products easily discoverable, useable, and understandable by citizen scientists.
- Develop applications for ecosystems and human health decision makers, who need timely information in NRT, in an easily accessible format, understandable, and trusted by their end users.
- Adopt a standard format for satellite products to increase usage, enhance collaboration, and minimize end-user impacts.

The complete conference proceedings are published at *https://directreadout.sci.gsfc.nasa.gov/?id=dspContent&cid=244*. ■

Summary of the Second GEDI Science Team Meeting

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Introduction

The second Global Ecosystem Dynamics Investigation (GEDI) Science Team Meeting took place September 21-23, 2016, at NASA's Goddard Space Flight Center (GSFC) in Greenbelt, MD. The meeting was attended by 25 members, collaborators, and associates of the GEDI science team. The main objectives of the meeting were to provide updates on engineering and mission progress, reports on the status of science algorithms, and to review mission calibration and validation activities, both internal to the GEDI science team as well as collaborative and cross-mission activities, such as the AfriSAR campaign.[1]

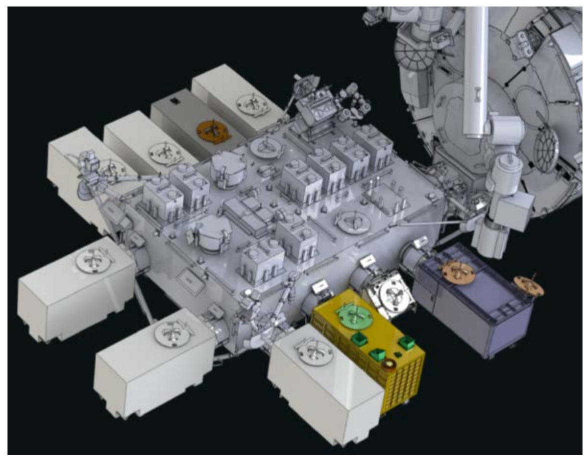
The GEDI Mission

The GEDI mission is one of two instruments chosen from the second Earth Venture Instrument (EVI-2) under the Earth Science Pathfinder Program.[2] GEDI is a multibeam lidar that will be installed on the Japan Experiment Module–Exposed Facility (JEM-EF) onboard the International Space Station (ISS) in late 2018—see **Figure 1**. GEDI will provide Earth's first comprehensive and high-resolution dataset of ecosystem structure—to learn more, see *GEDI: Using Lidar Waveforms to Measure Canopy Structure* on page 32. These data will advance our ability to characterize the effects of changing climate and land use on ecosystem structure and dynamics.

In particular, GEDI addresses three science questions:

- What is the carbon balance of Earth's forests?
- How will the land surface mitigate atmospheric carbon dioxide (CO_2) in the future?
- How does forest structure affect habitat quality and biodiversity?

Answering these questions is critical for understanding the future path of global climate change and Earth's biodiversity. GEDI will address these science questions by quantifying the current state of forest aboveground biomass; the net result of forest disturbance and subsequent recovery; the carbon sequestration potential of the land surface under conditions of changing land use; and the relationship between forest structure and biodiversity. To learn more about GEDI, visit *https://directory.eoportal.org/web/eoportal/satellite-missions/content/-/article/iss-gedi*.



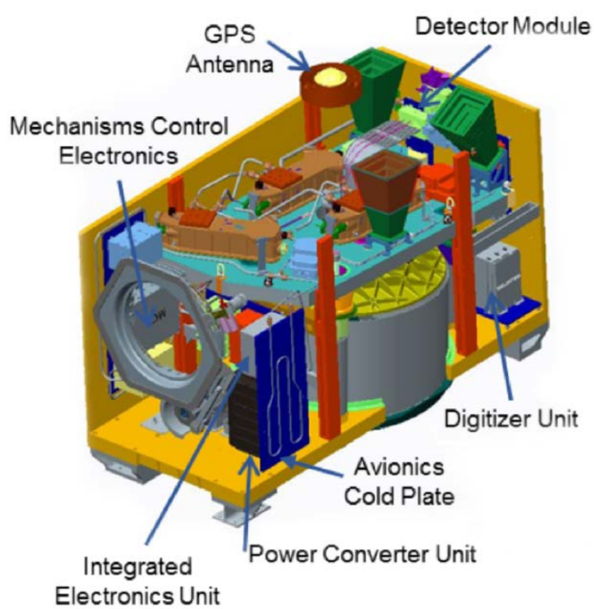


Figure 1. GEDI will be installed on the Japan Experiment Module–Exposed Facility (JEM–EF) onboard the International Space Station [*top*]. The image on the bottom is a schematic of the GEDI instrument showing the large honeycomb cylinder, which contains the beryllium mirror (facing down). The lasers are the three brown, rectangular boxes on top of the optical bench (in blue). The square, cone shapes are star trackers. **Image credit:** NASA

[1] The European Space Agency launched the first part of the AfriSAR campaign in Gabon, Africa in July 2015, collecting radar and field measurements of the country's forests. NASA and the German Aerospace Center [Deutsches Zentrum für Luft- und Raumfahrt (DLR)] joined the second leg of the campaign.

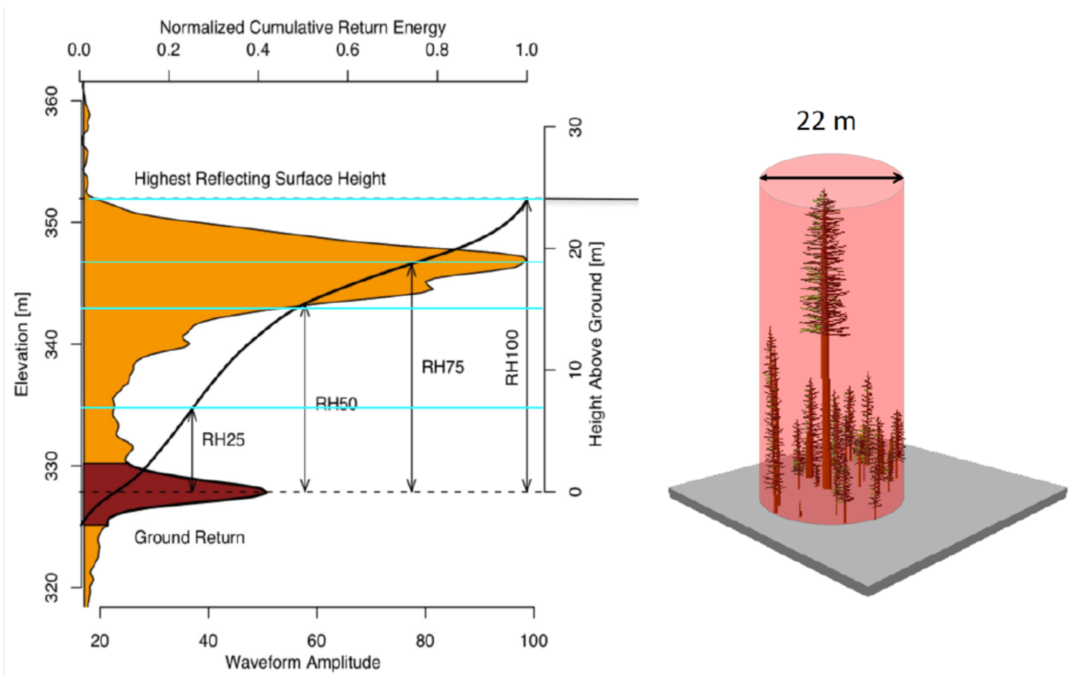
[2] The other instrument chosen was the ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS). To read about the most recent ECOSTRESS Science Team Meeting, see the March-April 2016 issue of *The Earth Observer* [**Volume 28, Issue 2**, pp. 24-28].

GEDI: Using Lidar Waveforms to Measure Canopy Structure

GEDI will address its mission science questions by making lidar *waveform* (i.e., vertical profile) observations between 51.6° N and S latitudes. Each GEDI laser shot will result in a waveform that contains information about the vegetation canopy and the topography underneath. Scientists will use this information to quantify canopy vertical structure, canopy height, and ground elevation. See **Table** on page 33 for a complete list of the planned GEDI Data Products.

The GEDI instrument—shown in Figure 1 on page 31—includes three identical laser transmitters. One will be used at full power, while the output from the other two will be split into two beams each, creating a total of five beams. Each of the beams will be optically *dithered** across-track to create a total of ten ground tracks, with between-track spacing of ~600 m (~1968 ft), and a total across-track width of 5.4 km (~3.4 mi). The average along-track distance between the footprints will be 60 m (~197 ft). The across-track dithering is fully programmable on orbit so that any pattern of along-track contiguous footprint patterns are possible. By the time the beam reaches the surface it has an approximate diameter—or *footprint*—of 22 m (~72 ft)—as illustrated below.

* Dithering of the beam creates two parallel ground tracks for each beam instead of one, which increases across-track coverage.



Shown here is sample GEDI lidar waveform [*left*]. The light brown area under the curve represents return energy from the canopy, while the dark brown area signifies the return from the underlying topography. The black line is the cumulative return energy, starting from the bottom of the ground return (normalized to 0) to the top of the canopy (normalized to 1). Blue horizontal lines are the *Relative Height (RH) metrics*, which give the height at which a certain quantile returned energy is reached. The schematic [*right*] shows incident near-infrared laser beam from GEDI interacting with a canopy. **Image credit:** Ralph Dubayah, University of Maryland College Park

Meeting Highlights

***Day 1:** Science Status*

The second Science Team Meeting builds on discussions that took place during the first meeting, which was held January 6-8, 2015, also at GSFC. The first meeting's foci were on developing data product algorithms, generating Algorithm Theoretical Basis Documents (ATBD), and assembling calibration and validation datasets.

Ralph Dubayah [University of Maryland, College Park (UMD)—*GEDI Principal Investigator*] convened the meeting, and began with an overview of the science status of the GEDI mission. He highlighted the mission's key science questions and how GEDI data products

Table. GEDI data products.

Product	Description	Resolution
Level-1	Geolocated waveforms	22 m (~72 ft) diameter
Level-2	Canopy height and profile metrics Relative height (RH) metrics Canopy top height Ground elevation Canopy cover and cover profile Leaf Area Index (LAI) and LAI profile	22 m (~72 ft) horizontal; 0.5 m vertical
Level-3	Gridded Level-2 Metrics	Nominal 1 km (~0.6 mi) grid
Level-4	Aboveground biomass **Demonstration products**: *Prognostic ecosystem model outputs* *Enhanced height/biomass using fusion with TanDEM X and Landsat* *Biodiversity/habitat model outputs*	22 m (~72 ft) footprint; 1 km (~0.6 mi) grid Grid size(s) TBD* Grid size(s) TBD Grid size(s) TBD

*Several Level-4 "demonstration" products are planned to be produced later in the mission; they will have various gridded sizes that will be specified at a later date.

will be used to address those questions—as summarized in **Figure 2**. He noted that GEDI was originally a one-year mission, but as a result of resource sharing with two other missions planned for future deployment on ISS—the Orbiting Carbon Observatory-3 (OCO-3)[3] and ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS)—it is now a two-year mission, but without change to its design parameters or mission objectives.

Jim Pontius [GSFC—*GEDI Project Manager*] then discussed the mission's engineering status. He reported that GEDI passed its mission Confirmation Review [Key Decision Point C (KDP-C)], and has entered into Phase C. Pontius extended congratulations to the science team and stated that the GEDI project has exhibited excellent financial performance and several important technical challenges have been solved since KDP-B. He emphasized that side-lobes in the transmitted laser beam—previously seen as a serious risk to the science mission requirements—have been successfully eliminated. In closing, Pontius gave kudos to the GEDI laser and engineering team for their outstanding work.

Bryan Blair [GSFC—*Deputy Principal Investigator and Instrument Scientist*] stated that the improved laser has been tested and has demonstrated flawless performance—well beyond the benchmark needed for the two-year mission. He then discussed how the team adapted the spare telescope mirror from the

[3] The OCO-3 instrument, planned for installation on the ISS, consists of three high-resolution grating spectrometers that will collect space-based measurements of atmospheric carbon dioxide.

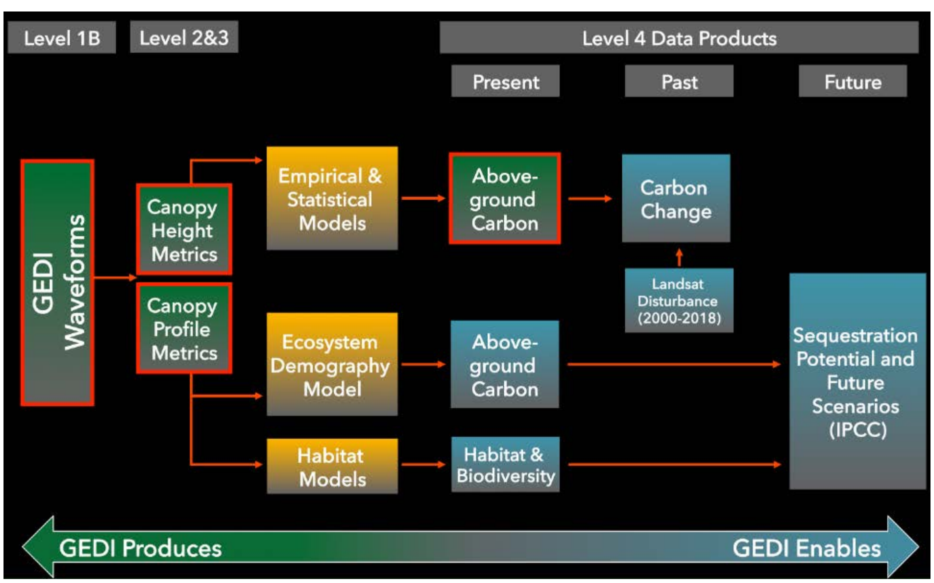


Figure 2. This diagram represents the relationship between GEDI data products and the GEDI science questions. **Image credit:** Ralph Dubayah, University of Maryland College Park

Ice, Cloud, and land Elevation Satellite-2 (ICESat-2) mission's Advanced Topographic Laser Altimeter System (ATLAS) lidar to work for the GEDI instrument—a major achievement. Another major improvement was the addition of flexible beam dithering that can be configured while in orbit to collect customized sampling patterns and provide new science opportunities.

Scott Luthcke [GSFC] outlined the status of the GEDI Science Data Management Plan and GEDI Science Operations Center. Key functionalities afforded by these systems include on-orbit direction changes through instrument pointing to acquire specific targets, e.g., permanent field plot locations, and controlling across-track dithering[4] during ISS orbits to increase along-track sampling density over specific targets. He also stated that algorithm dependencies and required ancillary products will be defined by the end of the year in preparation for the GEDI Critical Design Review, currently scheduled for early 2017.

Science Collaborations

The GEDI Science Team relies on the marriage of ground-based structure and biomass observations with Airborne Laser Scanning (ALS) observations to calibrate GEDI data products. In particular, the team has worked to develop equations that relate lidar footprint metrics to field-measured, aboveground biomass. GEDI scientists therefore participate in several ground networks to ensure the largest, most reliable, and complete dataset to calibrate models.

John Armston [UMD] provided an overview of the outcomes of the joint NASA and ESA workshop on the calibration and validation of forest aboveground biomass products from their future space missions. The workshop was organized by Smithsonian Institute, NASA, and ESA and was held at the Smithsonian Institution in Washington, DC, from May 31 to June 3, 2016. He also discussed the GEDI perspective on current plans to coordinate calibration/validation activities across ESA's Biomass[5] mission, the NASA-ISRO Synthetic Aperture Radar (NISAR) mission,[6] and the GEDI mission.

Crystal Schaaf [University of Massachusetts Boston] described the National Science Foundation (NSF) Terrestrial Laser Scanner (TLS) Research Coordination Network (RCN) as GEDI scientists will contribute to the generation of calibration datasets for tree volume and biomass modeling. She also discussed an RCN field exercise and instrument intercomparison planned for August 2017 at Harvard Forest, in MA. This is a Long Term Ecological Research (LTER) and National Ecological Observatory Network (NEON) site with extensive forestry data—which was recently overflown by the NEON Airborne Observational Platform[7]. The assembled GEDI scientists then discussed the importance of maintaining an active role within the ground-observation community to improve the calibration/validation dataset quality.

Presentations on the collaboration between GEDI and other missions followed. **Amy Neuenschwander** [University of Texas—*ICESat-2 Vegetation and Land Products Mission Lead*] discussed future ICESat-2 vegetation measurements. **Scott Luthcke** discussed a potential framework and computational methods for a fused product using GEDI and ICESat-2 measurements of canopy height and their uncertainties. **Laura Duncanson** [GSFC—*Science Co-Investigator on NASA's Carbon Monitoring System (CMS) HighBio Project*], explained how GEDI is embedded within this project, quantifying the uncertainties of estimating biomass in high-biomass regions between GEDI, NISAR, and ICESat-2.

Lola Fatoyinbo [GSFC—*AfriSAR Science Lead*] then discussed the results of the 2016 AfriSAR campaign, a collaboration between NASA, ESA, and German space agency [Deutsche Zentrum für Luft- und Raumfahrt (DLR)] focused on the estimation of biomass. Airborne SAR and lidar instruments were flown, including NASA's Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) and the Land, Vegetation, and Ice Sensor (LVIS),[8] which serves as the GEDI instrument simulator. Fatoyinbo stated that by all measures, the AfriSAR campaign was a great success and will provide a wealth of data to inform the upcoming missions. **Ralph Dubayah** added that the collaboration with DLR is ongoing and that plans are underway to work on fused data products using Synthetic Aperture Radar (SAR) interferometry from TanDEM-X[9] and GEDI lidar observations.

[4] Across-track dithering is used to change the configuration of the footprints, leading to increased along-track sampling density of specific targets.

[5] Biomass is the eighth mission funded under ESA's Earth Explorer Program. Currently scheduled for launch in 2021, it will provide global maps of how much carbon is stored in Earth's forests and how this stock is changing over time—mainly through absorption of carbon dioxide, which is released from burning fossil fuels.

[6] NISAR is a joint mission between NASA and the Indian Space Research Organization.

[7] The Harvard Forest site is comprised of 3750 acres (~1518 hectares) of land and multiple research facilities; it is the core NEON site for the Northeast region.

[8] LVIS is an airborne scanning altimeter instrument developed at GSFC; it has been operational since 1998. For more information, visit *http://lvis.gsfc.nasa.gov*.

[9] The DLR's TanDEM-X (TerraSAR-X add-on for Digital Elevation Measurements) mission, a successor to the TerraSAR-X satellite, was launched successfully on June 21, 2010, from Baikonur Cosmodrome in Kazakhstan. TerraSAR-X, launched in 2007, is a joint venture being carried out under a public-private partnership between the German Aerospace Center (DLR) and EADS Astrium. Flying in close formation only a few hundred meters apart, TanDEM-X and TerraSAR-X are imaging the terrain below them simultaneously, but from different angles.

GEDI Science Algorithms

GEDI data products are based on formal ATBDs. Each GEDI science product has an associated lead on the science team. **Scott Luthcke** explained that the Level-0 product involves decompressing and unpacking the received signal; processing and detailed calibration of the global positioning system (GPS), Star Tracker, and gyro data generates the Level 1B product—calibrated and geolocated waveforms. The current estimate of geolocation accuracy is ~7 m (~23 ft) horizontally; therefore, knowledge of the location of each laser footprint and geolocation error is critical.

Michelle Hofton [UMD] is leading the development of the Level-2 canopy height and ground height products. She described how the sensitivity of the ground-finding algorithm to noise is critical for the correct derivation of ground height, especially in areas with high canopy cover. She explained that her team is working with LVIS waveforms to develop and improve ground- and canopy-finding algorithms. **Hao Tang reported** on the Level-2 canopy profile metric products, which will provide estimates of canopy cover, LAI, vertical foliage profile, and foliage height diversity, using well-established algorithms. Lastly, **Bryan Blair** described the development of new data and waveform quality metrics and flags as part of the GEDI Level-2 data products. He concluded that these new metrics are critical to the proper utilization of the GEDI data and are therefore currently being tested on LVIS data.

Day 2: *Calibration and Validation Plans*

John Armston provided an overview of the GEDI calibration/validation plan, explaining that such activities for the Level-0 to -3 data products are relatively straightforward, given the community's long experience with waveform lidar, particularly with data from LVIS and ICESat-1, and the maturity of existing algorithms. Calibration for the Level-4 footprint–level, aboveground biomass product is accomplished prelaunch using globally collated field measurements of aboveground biomass and coincident ALS data, from which GEDI waveforms will be simulated. Armston concluded that the GEDI team terms this "crowd sourced calibration," as it relies mainly on datasets contributed from external sources.

Steve Hancock [UMD] provided detail on the *GEDI waveform simulator*—an algorithm that takes different types of ALS data and creates GEDI-type waveforms. Sufficient ALS datasets are now available to test the simulator thoroughly. The simulator also allows evaluation of the impact of factors that affect instrument performance on data accuracies.

Suzanne Marselis [UMD] provided a summary of the existing field data that have been acquired through crowdsourcing, providing field measurements of biomass with coincident ALS data across all biomes between 51.6° N and S latitude. Together these provide the pre-launch data used to calibrate empirical biomass models. **John Armston** highlighted the importance of taking into account the combined effects of geolocation error and the spatial mismatch between the GEDI footprint size and different plot sizes and shapes on the GEDI biomass calibration. Finally, **Hao Tang** discussed GEDI's global reprocessing of the ICESat dataset to globally characterize the distribution of canopy-cover conditions that GEDI will see, noting that active lidar provides superior estimates of cover in high-canopy-cover forests, compared to passive optical data. ICESat cover datasets were used to drive end-to-end simulations of expected sensor performance, confirming that GEDI data products will meet their Level-1 science requirements.

Level 4 Biomass Data Products

The discussions on algorithm development from Day 1 of the meeting continued with a discussion that focused on the biomass products. **Jim Kellner** [Brown University] described the algorithm status for the Level-4 footprint-level biomass product. He reported that the science team is systematically evaluating published and novel approaches to predicting aboveground biomass using lidar facilitated by coincident airborne lidar and ground-based field inventories where trees have been mapped and measured.

John Armston and **Suzanne Marselis** have developed a repository to manage code and data to associate simulated GEDI waveforms with field measurements. Prelaunch, simulated GEDI waveforms (produced using the GEDI waveform simulator that Steve Hancock, Bryan Blair and Michelle Hofton developed) will be used to create predictive models. Armston and Marselis also described a calibration software interface built on the R statistical platform, which will allow users to interactively explore and create calibration relationships. The science team is evaluating model types, the stratification of the world into regions or biomes, and the GEDI lidar metrics used in the model. To meet Level-1 science requirements, GEDI will create a 1-km (~0.6mi) gridded biomass product from the footprint-level model-based estimates.

Sean Healey and **Paul Patterson** [both from the U.S. Forest Service (USFS)] discussed statistical estimation processes for converting spatially discontinuous footprint estimates to areal biomass estimates. They explained that the process used by GEDI for gridding estimated biomass into 1-km (~0.6-mi) cells from individual footprints will expand upon sample-survey approaches first developed for airborne lidar support of forest inventories. Healey and Patterson also reported that testing of proposed mean biomass estimators is currently underway using simulation methods covering different numbers of GEDI footprints, different levels of variability at the GEDI grid scale, and different levels of footprint-level model accuracy, emphasizing that this work is carried out in collaboration with scientists from the Swedish University of Agricultural Sciences.

Day 3: *Level-4 Demonstration Products on Carbon Balance, Sequestration Potential, and Habitat Quality*

As noted earlier (see page XX) GEDI data enable important opportunities for vegetation studies other than biomass estimation, by producing example products for specified regions globally. **Patrick Jantz** [Northern Arizona University (NAU)] and **Scott Goetz** [NAU—*GEDI Deputy Principal Investigator*] described how footprint and gridded GEDI products will be made available to the biodiversity conservation research and applications communities, providing them with previously unavailable information on habitat structure from local to continental scales. They shared their thoughts on unique research opportunities that will be created by consistent information that will capture habitat changes through time, and the implications for international biodiversity conservation initiatives. **Matt Hansen** and **Chengquan Huang** [both from UMD] outlined a plan to use GEDI footprint-level biomass estimates in conjunction with Matt Hansen's Landsat disturbance dataset to quantify the net impact of deforestation and regrowth. They suggested that GEDI canopy structural information could potentially revolutionize ecosystem modeling by providing hitherto unavailable model initialization information on the status of forests—in particular, their height, successional state, and biomass. **George Hurtt** [UMD] discussed his efforts working with **Ralph Dubayah** over the last decade to marry canopy information from lidar with the Ecosystem Demography (ED) model. Their pioneering efforts have paved the way to global ecosystem modeling at 1-km (~0.6-mi) resolution using GEDI. Several large regions across the world will be chosen and the ED model will be initialized with data from GEDI to predict future changes in carbon under different land cover change scenarios.

Level-4 Enhanced Height, Biomass, and Topography Products using TanDEM-X

Seung-Kuk Lee [GSFC], **Lola Fatoyinbo, Wenlu Huang** [UMD], and **Ralph Dubayah** described their ongoing efforts with DLR counterparts exploring radar/lidar fusion, presenting results from experiments to estimate height using simulated GEDI data and TanDEM-X Random Vegetation over Ground (RVoG) modeling. The discussion that followed focused on identifying field sites to prioritize for further algorithm development.

AfriSAR Data Products

One of the key elements of AfriSAR is to provide calibration and validation data for missions such as GEDI. **Lola Fatoyinbo** gave an update on the status of the field and remote sensing data processing over the complex landscapes of Gabon. She stated that the data collected spanned exceptionally large gradients in canopy cover and biomass—ranging from savannahs to tropical forests to coastal mangrove forests—explaining that because of the extreme structural diversity and the high values of aboveground biomass, these should be extraordinary calibration/validation datasets for GEDI. Fatoyinbo added that some members of the GEDI Science Team also participated in the AfriSAR campaign and are responsible for producing core datasets. **Michelle Hofton** and **Bryan Blair** reported that they are on track to release the LVIS waveform, height, and topography products. They reported that LVIS was able to acquire over 90% of the target areas, despite the high cloud and haze conditions that are frequently present in Gabon. The LVIS dataset is particularly relevant for GEDI as LVIS data can be used to effectively simulate GEDI waveforms, and thus provide great insight into instrument sensitivities over the challenging environmental conditions in Gabon. **Hao Tang** stated that he will develop canopy profile products from the LVIS data and assess how these algorithms may be applied to GEDI data. **John Armston** and **Steve Hancock** added that they will focus on how to cross-calibrate and validate the canopy height and profile products with airborne and terrestrial laser scanning data. **Laura Duncanson** discussed how she will create an aboveground biomass product from the LVIS data and provide uncertainty analysis at both the footprint level and at a 1-ha spatial resolution. Finally, **Lola Fatoyinbo** talked about how she will perform cross-validation of LVIS and UAVSAR products.

Conclusion

The excitement around the first space lidar optimized specifically for vegetation continues to grow, as was evident from the reports from science team members and collaborators who attended the meeting. The meeting achieved its goals, enhancing understanding of the different aspects of the complex project among team members. Going forward, the near-term foci are on developing algorithms, continuing refinement of the end-to-end GEDI performance tool, and on expanding the calibration/validation database—the latter through enhanced cooperative and collaborative efforts such as GEDI's crowdsourcing approach and participation in joint experiments such as AfriSAR. ■

2016 Aura Science Team Meeting Summary

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Introduction

The 2016 Aura science team meeting was held in Rotterdam, Netherlands, from August 30 to September 1, 2016. The Royal Netherlands Meteorological Institute [Koninklijk Nederlands Meteorologisch Instituut (KNMI)]—the principal investigator (PI) organization for Aura's Ozone Monitoring Instrument (OMI)—hosted the meeting. There were 106 registered participants representing government, academic, and commercial institutions located in seven different countries. The purpose of the meeting was to discuss new science results, validation activities, algorithm improvements, and to review the performance of Aura's instruments. The science portion focused on Aura's three themes: air quality, climate, and stratospheric ozone.

The meeting opened with introductory remarks by the head of the Netherlands Space Office, **Ger Nieuwpoort**, who acknowledged Aura achievements, and was particularly gratified that OMI was able to provide groundbreaking data relevant to Aura's main themes. He went on to discuss the upcoming TROPOspheric Monitoring Instrument (TROPOMI), which is being developed in the Netherlands and will fly on the European Space Agency's Sentinel-5 Precursor mission, scheduled for launch in March 2017. TROPOMI has advanced capabilities that were derived from OMI. The second introductory talk was by the Rotterdams's Deputy Resilience Officer, **Wynand Dassen**, who described how the city was rebuilt after being flattened by the Nazis in World War II. He emphasized that Aura data clearly show that Rotterdam is one of the cleanest cities in Europe, despite being the largest industrial city in the Netherlands, the largest port in Europe, and the third busiest port in the world.

As a further introduction to the meeting, **Ken Jucks** [NASA Headquarters—*Aura Program Scientist*] provided an overview of missions pertinent to the Atmospheric Composition program in NASA's Earth Science Division, reminding the group about the upcoming Aura Senior Review. He also discussed the status of plans for upcoming missions, including the Orbiting Carbon Observatory-3, to fly on the International Space Station, and the Tropospheric Emissions Monitoring Pollution (TEMPO) instrument (an Earth Venture).[1] Finally, Jucks discussed the upcoming U.S. National Academy of Science's 2017 Earth Science Decadal Survey.[2]

This article is organized by first summarizing the PI reports on the performance of the three instruments [OMI, Microwave Limb Sounder (MLS), and Tropospheric Emission Spectrometer (TES)], then highlighting science results addressing Aura's three science themes; summarizing algorithm refinements and validation activities; and reviewing the two Working Groups' reports. There were 54 oral presentations and 31 poster papers. Not all are described here; the author chose to focus on those most easily described to *The Earth Observer*'s readers. Most of the presentations can all be found at *http://avdc.gsfc.nasa.gov/index.php?site=1072744097*.

Instrument Status – Twelve Years in Orbit

Three of Aura's four original instruments[3] continue to function nominally; however, TES is about to reach the end of its expected life. Aura data are being widely used by the science and applications community, and in many instances Aura data are being applied in conjunction with data from other instruments that fly onboard satellites that make up the Afternoon Constellation, or A-Train.[4]

Ozone Monitoring Instrument (OMI)

Pieternel Levelt [KNMI—*OMI PI*] reported on behalf of the OMI Science Team. She reviewed the instrument's performance since Aura's launch in 2004, and described two anomalies that happened in the past year, both of which were easily corrected. The detector-row anomaly has remained unchanged or accounted for since it first occurred in 2007. The instrument has been extremely stable, making it highly suitable for ozone and solar irradiance trend analysis. Levelt provided an overview of OMI science results, showing how OMI data have been used to study global and regional air-quality trends, how analysis of the data have led to the discovery of pollution sources that were previously not part of the global inventory, and how aerosol

[1] To learn more about the mission, please refer to "NASA Ups the TEMPO on Air Quality Measurements" in the March–April 2013 issue of *The Earth Observer* [**Volume 25**, **Issue 2**, pp. 10-15, 35].

[2] To learn more about the Decadal Survey, visit *http://sites.nationalacademies.org/DEPS/ESAS2017/index.htm*.

[3] The fourth instrument was the High Resolution Dynamic Limb Sounder (HIRDLS), which ended its mission in 2008.

[4] To learn more about the satellites and instruments that make up the A-Train, visit *http://atrain.nasa.gov*.

data from MODIS[5] and CALIOP[6] have been used to improve OMI aerosol products. She also reported that OMI air-quality data products are now being used in U.S. Environmental Protection Agency (EPA) reports. Finally, Levelt announced that a special joint issue of *Atmospheric Measurement Techniques* and *Atmospheric Chemistry and Physics* is under review and focuses on 10 years of OMI observations.

Joanna Joiner [NASA's Goddard Space Flight Center (GSFC)—*Aura Deputy Project Scientist*] gave an overview of U.S. OMI activities. These included developing products that benefit OMI algorithm developers and the broader ultraviolet-visible (UV-Vis) remote-sensing community, and updates on calibration/validation activities and other data products. Noteworthy among these is a trend-quality total-ozone algorithm, an advanced sulfur dioxide (SO_2) algorithm compatible with other UV-Vis instruments, application of MODIS data to improve OMI aerosol and cloud products, radiative transfer codes needed for these applications, and climate-quality solar irradiance data. Investigators from both sides of the Atlantic discussed these topics in more detail in subsequent sessions.

Microwave Limb Sounder (MLS)

Nathaniel Livesay [NASA/Jet Propulsion Laboratory (JPL)—*MLS PI*] explained that while some subsystems are showing signs of aging—expected after 12 years in orbit—overall the MLS instrument is running quite well and producing high-quality science data. The team is conducting a rigorous study of systematic errors. Livesay highlighted results that included a decade of very-high-stability MLS ozone-profile data; he also showed crucial water vapor data for climate studies (showing some as yet unexplained trend differences with respect to ground measurements). Livesay also showed data that indicates (HCl), a tracer for anthropogenic chlorine in the stratosphere, has resumed a slow decline, indicating that anthropogenic sources such as chlorofluorohydrocarbons (CFCs) have declined in the troposphere.

Tropospheric Emission Spectrometer (TES)

Kevin Bowman [JPL—*TES PI*] described the performance of TES, which is degrading at a rate in keeping with prelaunch estimates. He stated that the laser is now unable to produce sufficient power to generate detectable *interferograms,* which are converted to Earth spectral radiances. Bowman added that in keeping with the best traditions of remote sensing and resilience, the TES science team has developed and is testing a *simulated clock algorithm*—a routine based upon measurements of time, rather than of space—as an alternative way to collect and process these laser measurements to produce interferograms. He explained that testing will take several months, with consequent delay of data product delivery. TES continues to collect and transmit raw data to the ground during Special Observation modes. Bowman also highlighted several science topics that are reported in more detail in *Science Highlights* that follow.

Science Highlights

The highlights presented here focus on the Aura mission's three science themes, as noted earlier: air quality, climate, and stratospheric ozone.

Air Quality

OMI has revolutionized air-quality observations with its global coverage and high spatial resolution. Consequently, presentations about air quality dominated the meeting and covered trends, cross-continental transport, local pollution, and applications relevant to policy. The OMI instrument has clearly shown an improvement in regional air quality over the U.S. and Western Europe. Some of the presentations explored connections between air quality and Aura's other themes: stratospheric ozone and climate.

Jessica Neu [JPL] presented a poster that demonstrated the results and application of a tropospheric ozone product that combines multispectral TES and OMI radiance data using an optimal estimation algorithm. She stated that in some cases, TES/OMI retrievals averaged over the near-surface layer showed a better correlation with ozonesonde measurements averaged over the same layer than either TES or OMI separately. To conclude, she said that a more detailed comparison is being performed using the EPA's Community Multiscale Air Quality (CMAQ) model.

Willem Verstraeten [Royal Meteorological Institute of Belgium] presented a poster that complemented Neu's finding. He described how his team investigated the rapid increases in tropospheric ozone levels over China using data from all three of Aura's operational instruments. They compiled short-term time-series of Aura tropospheric ozone data for eastern China

[5] MODIS stands for Moderate Resolution Imaging Spectroradiometer, which flies on NASA's Terra and Aqua platforms.
[6] CALIOP stands for Cloud–Aerosol Lidar with Orthogonal Polarization, which flies on the Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) mission, a joint effort between NASA and CNES, the French space agency.

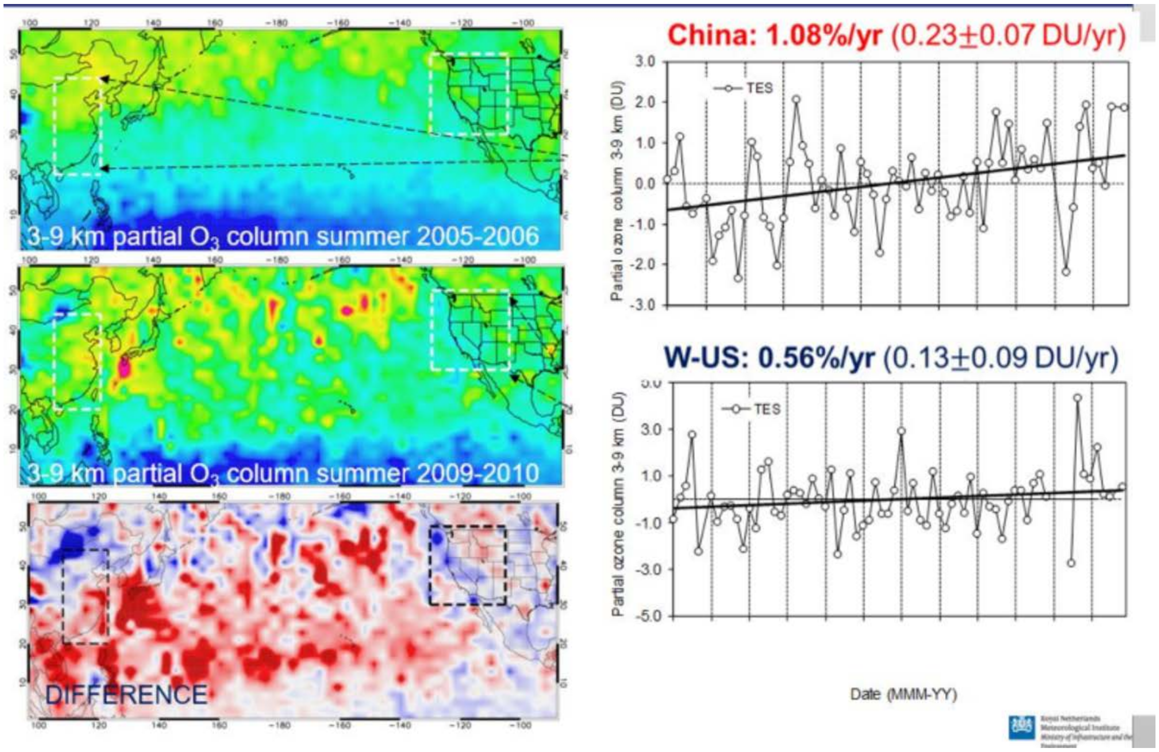

Figure 1. The figures show where and by how much tropospheric ozone (O_3) has changed for the period 2005 to 2010 over Eastern China and the Western U.S., using TES data. The maps on the left show [*top*] ozone amounts in the middle troposphere for 2005-2006, [*middle*] ozone amounts in the middle troposphere for 2009-2010, and [*bottom*] the difference between the two, where red shades indicate increases in tropospheric ozone and blue shades indicate decreases. The plots on the right show change as a function of time. **Image credit**: Meteorological Institute of Belgium

and the Western U.S.—see **Figure 1**. Using a chemical transport model, he said that the team found that ozone trends in the troposphere over China could be attributed to stratospheric-tropospheric exchange and anthropogenic sources. Verstraeten also showed that some of the ozone reduction in the western U.S., resulting from pollution control, is offset by transport of ozone from China. To conclude, he stated that their findings are a reminder that atmospheric pollution is not limited by political borders, and is therefore truly an international issue.

Karen Cady-Pereira [Atmospheric and Environmental Research (AER)] presented results that illustrated how well TES can detect pollution over *megacity*[7] regions. She reported that by measuring gas emitted from combustion sources, data from TES can be used to determine amounts of pollution from different sources, such as biomass burning, engine combustion, and meteorological influences.

Other presentations on the air quality science theme demonstrated how data from TES will contribute to the Tropospheric Ozone Assessment Report to be released by the International Global Atmospheric Chemistry Project. Also, **Helen Warden** [University Corporation for Atmospheric Research (UCAR)] included comparisons of TES, IASI,[8] and combined OMI-MLS global tropospheric ozone levels, which revealed some biases, although the global patterns were similar.

Lu Hu [Harvard University] illustrated OMI's ozone mapping capability by explaining how meteorological-deep convection, clouds, temperature, and chemical processes influence global tropospheric ozone using the GEOS-Chem model.[9] Hu explained that extensive validation, using data from ozonesondes, found no significant bias relative to OMI data at low and middle latitudes, but did show a negative bias at high northern latitudes.

Several presentations focused on OMI nitrogen dioxide (NO_2) measurements since it is a precursor to the formation of ozone in the troposphere. **Daniel Jacob** [Harvard University] on behalf of **Kathrine Travis** [Harvard University] showed how NO_2 transported down from the upper troposphere affects OMI NO_2 data as top-down constraint on U.S. emissions of oxides of nitrogen (NO_x). Based on extensive comparisons

[7] A *megacity* is usually defined as a metropolitan area with a total population in excess of ten million people.

[8] IASI stands for the Infrared Atmospheric Sounding Interferometer, which flies on the European Space Agency's MetOp series of satellites.

[9] 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 GSFC's Global Modeling and Assimilation Office.

taken during aircraft campaigns, she found that, in some cases, U.S. EPA National Emissions Inventory of NO_x emissions are too high by a factor of two.

OMI observations have shown a dramatic decrease in NO_2 over China since about 2010. **Fei Liu** (KNMI) explored this decrease with a synthesis of satellite observations and emission inventories, to examine regional trends. Electricity production and coal consumption remained constant, so these factors alone could not explain the decline in NO_2 levels, which suggests that emission control measures have been effective.

Willem Verstraeten described how his team used a top-down approach to investigate NO_X emissions over European cities. Specifically, they used a method that takes into account the effects of winds on observed NO_2 distributions. He stated that the results were in good agreement with Europe's Monitoring Atmospheric Composition & Climate project (*http://www.gmes-atmosphere.eu*), and show that—like China—Europe has also seen a decrease of atmospheric NO_2 concentrations, but beginning much earlier than Liu suggests for China.

In addition to ozone and NO_2, OMI measures indicators of volatile organic compounds (VOCs) that result from burning forests. **Peter Zoogman** [Harvard-Smithsonian Center for Astrophysics] presented results that describe how land cover and seasonality affect biomass-burning emissions, showing that increases in formaldehyde (HCHO) and glyoxal (CHOCHO) are associated with fire activity. The seasonal signal for these enhancements can differ for different forest types or yearly conditions, and the land-type burned can strongly influence the timing of these enhancements. Complementing these results, **Min Huang** [University of Maryland College Park] showed relationships between land (soil moisture) and air quality conditions using data assimilation and chemical transport models. OMI data, European satellite HCHO data, and MODIS aerosol data were used to constrain these assimilations.

Lightning is a source of NO_x in the upper stratosphere and needs to be accurately accounted for in the tropospheric ozone budget to accurately document emission inventories. **Ken Pickering** [GSFC] described the development of a special OMI algorithm to detect lightning-generated NO_2. His results show evidence for increased production per flash with lower flash rates, consistent with other values in the literature range.

Chris Mclinden [Environment and Climate Change Canada] earlier found that there are missing sources in the established emission inventories using OMI SO_2 data, an observation that received media attention. In a poster, McLinden further explained that OMI is able to detect and quantify emissions of SO_2 that did not appear in conventional emissions inventories. These 39 heretofore-unaccounted-for sources originated in volcanoes, smelters, and oil fields. Using OMI data, he and his group created a global SO_2 inventory that is complementary to "bottom-up" inventories.

In a surprising result, **Bryan Duncan** [GSFC—*Aura Deputy Project Scientist*] showed that despite a 44% decrease in NO_2 over the Washington, DC–Baltimore, MD area (observed by OMI), sensitive plants growing in Aura's "Ozone Garden"[10] located at GSFC's Visitor Center continue to show injury due to ozone. Duncan concluded that while ground-level ozone levels measured at a local agricultural station are lower than similar measuremenst made a decade ago, they are still high enough to cause ozone injury to certain plants.

Climate

Jonathan Jiang [JPL] described how satellite data are used in the World Climate Research Program's Coupled Model Intercomparison Project (CMIP),[11] stating that water vapor and ice cloud measurements and simulations were used as examples for CMIP model evaluation and improvement projects. **Hui Su** [JPL] described how she used CMIP5 to simulate present-day upper-tropospheric (UT) water vapor variations to explore long-term change under global warming conditions. She reported that one of her findings is that for interannual variations, the intermodel spread in UT water vapor sensivity to surface temperature is dominated by model differences in how they simulate relative humidity variations. Further, she found that tropical UT and lower stratosphere (LS) water vapor and UT clouds can alter surface radiative forcing and increase polar ozone loss.

Mark Schoeberl [Science and Technology Corporation] described how he used the MERRA-2[12] cirrus and gravity wave model and satellite data from MLS and CALIOP to conclude that UT/LS water vapor is controlled by tropopause temperature, the nucleation threshold for cloud relative humidity, and convection. Using TES data and model calculations, **Le Kuai** [UCLA] explained how she explored the control of the tropospheric ozone greenhouse effect by water vapor, clouds, temperature, and ozone levels. She discovered that the tropospheric ozone effect is low in the tropics, but maximized in subtropical regions in both hemispheres. Moreover, she demonstrated that relative humidity is a useful quantity to help identify the primary driver—the large-scale circulation—which determines water vapor, temperature, and cloud distribution.

The Asian summer monsoon (ASM) is the dominant climatological feature of UT/LS circulation during

[10] The primary purpose of the Ozone Garden is to engage the public and inform them about the impact of poor air quality on vegetation.
[11] For more information on CMIP, visit *http://cmip-pcmdi.llnl.gov*.
[12] MERRA-2 stands for Modern-Era Retrospective analysis for Research and Applications, Version 2.

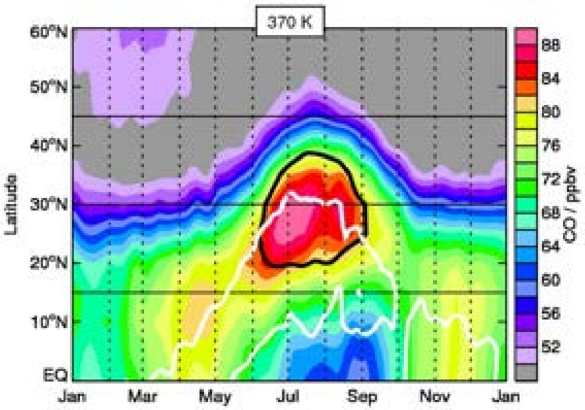

Figure 2. This contour illustrates a time series over the annual cycle as a function of geographic latitude for the period 2005–2014 for the Northern Hemisphere. Zonal averages of carbon monoxide are calculated over 10–130° E longitude [about 15 km (~9 mi)] from MLS CO at 370 K. The black overlay depicts the evolution of the closed circulation of the Asian Summer Monsoon (ASM) anticyclone. White contours indicate the occurrence of strong deep convection as determined by MLS measurements of ice water content (IWC). **Image credit:** JPL

boreal summer, and therefore has a strong impact on global atmosphere chemistry and transport, as well as the intensity of the monsoon rainfall. **Michelle Santee** [JPL] described how she used 10 years of MLS data to characterize the climatology of UT/LS trace gas distributions, such as water vapor, ozone, and carbon monoxide (CO), in the ASM region and quantify their spatial and seasonal variability. Based on monthly averages, she characterized the ASM seasonal dynamic using several trace gases measured by MLS. **Figure 2** is an example of this seasonality using CO as tracer. CO is entrained from biomass burning in Africa in the months prior to its maximum in July–August.

Mian Chin [GSFC] showed how she used model simulations to study sources and the role of ASM transport of natural and anthropogenic aerosols in the UT/LS. She explained that the models are validated using CALIOP, SCIAMACHY,[13] and OSIRIS[14] aerosol data. Examples of the simulations include volcanic aerosols that dominate the total stratospheric aerosol load, anthropogenic aerosols that exhibit well-organized seasonal cycle in the tropopause region, and strong convection in the subtropical Northern Hemisphere, which makes transport of aerosols to UT/LS most effective in the summer.

The excellent radiometric stability of OMI enabled **Sergey Marchenko** [GSFC/Science Systems and Applications, Inc.] to characterize both short-term (solar rotation) and long-term (solar cycle) changes in the solar spectral irradiance, which are components of climate forcing. He analyzed OMI data for the present solar Cycle 24 in the wavelength range 265-500 nm using complementary measurements from GOME-2[15] and the Solar Stellar Irradiance Comparison Experiment (SOLSTICE) and Spectral Irradiance Monitor (SIM) flying on the Solar Radiation and Climate Experiment (SORCE) satellite, and found that OMI results agree well with solar irradiance models from the Naval Research Laboratory and the German Max Planck Institute for Solar System Research. The long-term accuracy of OMI data is required for climate studies and therefore necessitates ongoing instrument calibration to maintain the utility of the data record.

The UCAR Whole Atmosphere Community Climate Model (WACCM-D) incorporates the chemistry of the D-region of the ionosphere[16] to reproduce the neutral atmospheric effects caused by solar-induced energetic particle precipitation in the polar region. **Monika Andersson** [Finnish Meteorological Institute] using WHACCM-D, constrained by MLS and ACE[17] satellite data—and with the inclusion of ion chemistry—showed significantly improved response of relevant neutral gas constituents to the energetic particle precipitation as compared with a model without D-region chemistry. She noted that it is necessary to include medium-energy electrons in the models to fully understand the sun–Earth connections[18] through particle precipitation.

Stratospheric Ozone

Because of the importance of verifying the terms of the 1987 Montreal Protocol to reduce ozone-generating species, validation of satellite data continues to be an important effort. Several decades of satellite ozone data are now available, along with concurrent measurements of chemically active atmospheric constituents obtained over the last 10 years by Aura. Contributions to such activities come from datasets from NASA's Upper Air Research Satellite (UARS) and Nimbus satellites that date back even farther.

Guanyu Huang [Harvard-Smithsonian Center for Astrophysics (HSCA)] reported on his results of studying a 10-year (2004-2014) OMI ozone profile dataset using Profile Ozone (PROFOZ), an HSCA algorithm, and compared the profiles with ozonesonde and MLS observations. He reported that the profile data show good agreement with ozonesondes in the tropics and

[13] SCIMACHY stands for SCanning Imaging Absorption SpectroMeter for Atmospheric CHartographY, which flew on ESA's Environmental Satellite (ENVISAT).

[14] OSIRIS stands for Optical Spectrograph and InfraRed Imager System, which is one of two instruments on the Swedish Odin satellite.

[15] GOME stands for Global Ozone and Monitoring Experiment (GOME-2), which flies on ESA's MetOp satellite series.

[16] The D-region of the ionosphere is the lowest of three regions in the ionosphere (D, E, and F); the D-region is the most energetic, as it absorbs hard X-rays and includes ionization that occurs below ~90 km (~60 mi).

[17] ACE stands for Atmospheric Chemistry Experiment, which is the main payload on the Canadian SciSat-1 satellite.

[18] Sun-Earth connection is a term used to describe solar activity effects on the magnetosphere, D-region ion and neutral chemistry, heating, and atmospheric circulation.

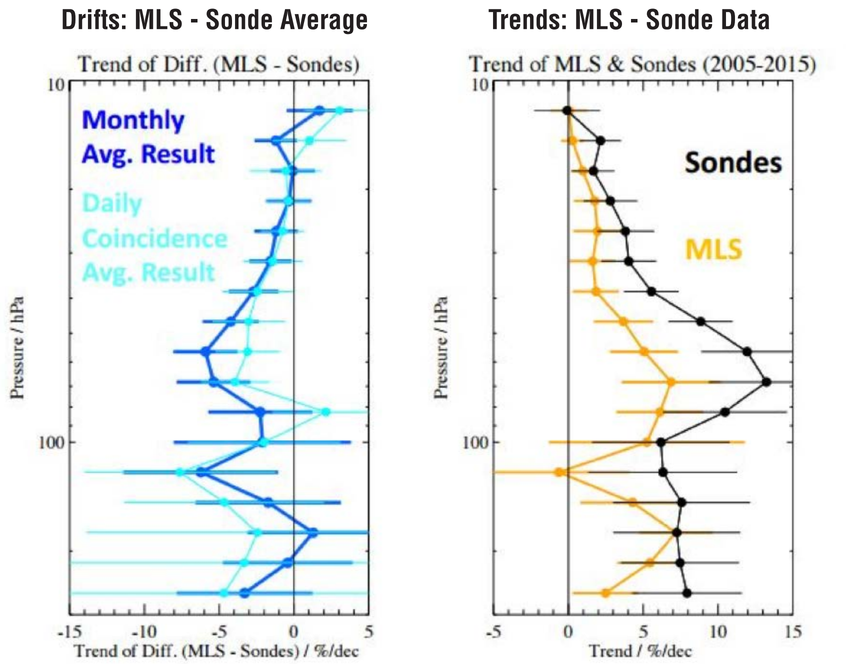

Figure 3. These plots show the results of an analysis of MLS versus ozonesonde data over a 10-year period. The figure on the right shows the trend in ozone profiles for both MLS and sonde data over the tropics—indicating an ozone increase, or recovery of roughly 0.5% per year. The figure on the left shows the difference between MLS and ozonesonde data, and how that difference changes over time. There is an indication that the trends differ, but with little statistical significance. **Image credit:** Lucien Froidevaux, JPL

mid-latitudes and above ~20 km (~12 mi) in the high latitudes. He added that when the data are compared to data from MLS, very good agreement occurs during 2004–2008, but the agreement is worse in the 2009–2014 data at Northern high latitudes and high altitudes. Huang suggested that more work is needed for OMI calibration in the later years.

Lucien Froidevaux [JPL] described how his team studied ozone variability and tendencies in the UT and LS based on Aura MLS and ozonesonde data. He stated that the specific goal of the study was to determine if the data are accurate over time to determine whether ozone continues to decrease or if levels have begun to increase. They focused their analysis at low latitudes using balloon ozonesondes—see **Figure 3**—and on consistency between MLS radiometric bands. He reported that data from MLS and sondes are found to be consistent and their errors are close to the expected trend. To conclude, Froidevaux stated that unambiguous detection of a long-term trend of < 2% per decade will remain challenging.

Kaley Walker [University of Toronto—*Atmospheric Chemistry Experiment (ACE) PI*] reviewed the status of and summarized recent results from ACE. The mission is, as she put it, "aging gracefully," and operations have been approved to continue to March 2018. Walker presented a variety of results that included volcanic influences on UT water vapor, global distribution of CO species that differ in isotopic composition, climatology for a variety of atmospheric constituents over space and time, and comparisons with chemical transport models, such as GEOS-Chem.

Patrick Sheese [University of Toronto] performed an analysis of drift between ACE and MLS atmospheric profile data, as the two instruments measure several of the same species, from the UT to the mesosphere. For ozone comparisons, ozonesonde data were included. While for the most part there is good agreement between the instruments over time for some constituents and high-altitude ranges, differences are in the range of ±2–4%, depending on the atmospheric species compared and the altitude range.

Krzysztof Wargan [GSFC] discussed how using Aura data affect MERRA-2 results for ozone and temperature. MLS and OMI data are assimilated into MERRA-2, then compared to MIPAS,[19] SAGE-2,[20] and ozonesonde data. These results show a good representation of the spatial and temporal variability of stratospheric ozone profiles, particularly in the UT/LS and up to the stratopause. Wargan encouraged researchers to use MERRA-2 ozone data in future studies.

Validation and Algorithms

Thirteen presentations illustrated improvements in Aura's data products and their applications. The data product improvements were to the OMI and TES algorithms, primarily, but used MLS data for comparisons. Some papers showed how these algorithms could be used for upcoming missions where they operate in wavelength ranges that are are similar to those covered by OMI and TES. What follows is a sample of those

[19] MIPAS stands for Michelson Interferometer for Passive Atmospheric Sounding, which flew on ESA's Enviornmental Satellite, Envisat.
[20] SAGE-II stands Stratospheric Aerosol and Gas Experiment II, which flew on NASA's Earth Radiation Budget Satellite (ERBS).

presentations. Please refer to the website referenced in the *Introduction* for more complete coverage of these topics.

As an example of an enhanced application of OMI NO_2 data, **Nickolay Krotkov** [GSFC] described a new OMI NO_2 Standard Product that removes bias in stratospheric NO_2. Comparison with independent satellite and ground-based data showed improvement because of reduced spectral fitting and *a priori* profile shape errors. This new product results in NO_2 levels that are more consistent with known emission inventories.

The Ozone Mapper Profiler Suite (OMPS) nadir mapper on NASA's Suomi National Polar-orbiting Partnership spacecraft is being used to further extend the record of ozone mapping started by the Total Ozone Mapping Spectrometer (TOMS) on Nimbus-7, and continued by subsequent TOMS instruments on other platforms and by OMI on Aura. **Richard McPeters** [GSFC] presented a poster that demonstrated how the TOMS version 9 algorithm is being applied to the over 10-year record of OMI ozone observations. Compared to data from the Solar Backscatter Ultraviolet (SBUV/2) instrument on the National Oceanic and Atmospheric Administration's (NOAA) NOAA-19 spacecraft,[21] total column ozone revealed a bias of about 1% where OMI is low. McPeters noted that agreement with the current OMI ozone algorithm for the OMPS nadir mapper is better than 0.5%. As he said, by using OMPS ozone data to extend the OMI mapper data record, "we will have a consistent record of spatial variation of ozone for years to come."

Yang Wang [Max-Planck-Institut für Chemie (Max Planck Institute for Chemistry)—Germany] reported on his team's study of how coincidence criteria affect the quality of comparisons of tropospheric composition measurements, such as clouds and *a priori* profiles using MAX-DOAS[22] ground-based observations in Wuxi, China. They found that spatial coincidence area has much stronger impact than coincident time. For OMI, 20 km (~12 mi) is optimal. They also found that clouds cause large uncertainties including biases, resulting from errors in calculated *a priori* profiles.

Robert Herman [JPL] presented a poster that demonstrated the results of testing the TES tropospheric ozone algorithm by comparing the results with ozonesonde data. The validation period ran from 2005 to 2016 and ranged from 30 °S to 50 °N latitude. The results indicate that TES has a bias ranging from roughly 5 to 15% in the LT and UT where sign of the bias depended on altitude. The standard deviations were roughly 20%.

[21] NOAA-19 (known as NOAA-N′ before launch) is the last in the series of Polar-orbiting Operational Environmental Satellites.

[22] MAX-DOAS stands for Multi Axis Differential Optical Absorption Spectroscopy, which contributes to the algorithm used to retrieve atmospheric composition from ground- and space-based instruments.

Kevin Bowman, who gave a presentation on behalf of **Dajian Fu** [JPL], described how the MUlti-SpEctral, MUlti-SpEcies, MUlti-SatEllite (MUSES) retrieval algorithm, which ingests observations across the range from ultraviolet to thermal infrared wavelengths (0.3 to 15 µm) across multiple platforms, in a nonlinear optimal estimation framework, could distinguish trace gases in the lower and upper troposphere. The algorithm can be employed in this wavelength range over combinations of eight instruments on four satellites, in orbit or soon to be in orbit. Bowman showed several examples that illustrated how combined measurements produce data products (such as ozone, CO, and methane) with better coverage and spatial resolution than could be obtained without such usage.

Working Group Reports

Data Systems

The Data Systems Working Group's reports summarized seven presentations from GSFC, JPL, and KNMI. These presentations consisted of a report from representatives of the Earth Science Data and Information System (ESDIS), ground data system reports from each instrument team, some new guidelines for use of the Hierarchical Data Format for the Earth Observing System (HDF-EOS), discussions on data preservation efforts, and evolving metadata requirements. The ESDIS presentation included the volume of data products distributed for each instrument and their trends over time; ESDIS tracked about 20,000 Aura users, their geographical distribution, and amount of data downloaded. Other data services and policies were also reviewed in the ESDIS report.

The report continued with an explanation of the Earthdata Login website site (*https://earthdata.nasa.gov*), which is a single portal for user management for users of the Earth Observing System Data and Information System (EOSDIS) system components (e.g., Distributed Active Archive Centers (DAAC), Worldview, and other tools and services) and is being implemented across all EOSDIS DAACs. There was also discussion of a new web interface to provide easier access to Aura data using updated Goddard Interactive Online Visualization ANd aNalysis Infrastructure (GIOVANNI)[23] visualization and analytic capabilities. These changes and guidelines will help users not only to discover the existence and nature of available data, but also to better understand them.

Mission Operations

The objectives of the Mission Operations Working Group at the Aura science team meeting were to discuss current spacecraft and instrument trends and preparations for the 2017 Senior Review for continued

[23] To learn more about GIOVANNI, visit *http://giovanni.gsfc.nasa.gov/giovanni*.

mission operation and data collection. **Dominic Fisher** [GSFC—*Aura Missions Director*] reported on several topics of interest to those involved in spacecraft and instrument operations, and stated that all spacecraft subsystems are performing nominally, and are configured to use primary hardware—i.e., no "backups" are being implemented. Fisher also reported on several events that affect operations but without negative consequences, and noted that there is sufficient fuel to maintain Aura as part of the A-Train at least through 2020 and likely beyond. With regard to data capture, Fisher reported that rates were "stellar," i.e., 99.99% successful with no losses or operations error in the last five years.

Summary

The meeting attendees agreed that the meeting went quite well and all enjoyed Rotterdam's hospitality. The meeting provided opportunities for productive, face-to-face discussion amongst the science team members, since some members are separated by the Atlantic Ocean as they work on common topics and issues in science, algorithms, and validation efforts. OMI and TES continue to yield significant science results that are being applied by operational environmental protection agencies for air quality assessments, regulations, and forecasts, both in the U.S. (EPA) and Europe. Although Aura does not measure carbon directly, it is making substantial contributions to understanding climate change by measurements of other climate forcing factors, such as, water vapor, solar irradiance, and aerosols. OMI and MLS continue their crucial observations in the stratosphere that are needed for monitoring compliance of the Montreal Protocol. Several of the presentations on climate an air quality demonstrated synergy between Aura and other missions in the A-Train. Aura has been in orbit for 14 years, and although some instruments are "aging gracefully", the results from this meeting are a testament that the mission continues to contribute new science results that are being applied to studies of air quality, climate, and stratospheric ozone. ■

Storytelling and More: NASA Science at the 2016 AGU Fall Meeting

Please plan to visit the NASA booth (#535) during the American Geophysical Union's (AGU) forty-ninth annual Fall Meeting. This year the exhibit hall will open on Monday, December 12, and will continue through Friday, December 16.

NASA Science has a story to tell and, at AGU, you can be part of it! This year's exhibit will feature daily storytelling Hyperwall presentations, flash talks, hands-on demonstrations, and more—covering a diverse range of topics including Earth science, planetary science, and heliophysics. New this year, the winners of the *2016 AGU Data Visualization Storytelling Competition** will present their winning visualizations on the Hyperwall from 12:00 – 1:00 PM on Tuesday, December 13 and Wednesday, December 14.

A daily agenda will be posted on the Earth Observing System Project Science Office website—*eospso.nasa.gov*—in early December.

We hope to see you in San Francisco!

*For more information about the competition and to see a list of the winners, visit: *https://education.agu.org/grants/data-visualization-storytelling-competition/award-information.*

A NASA Science presentation using the dynamic Hyperwall display during the 2015 AGU Fall Meeting. **Image credit:** NASA

Landsat Science Team: 2016 Summer Meeting Summary

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Introduction

The summer meeting of the joint U.S. Geological Survey (USGS)-NASA Landsat Science Team (LST) was held July 26-28, 2016, at South Dakota State University (SDSU) in Brookings, SD. LST co-chair **Tom Loveland** [USGS's Earth Resources Observation and Science Center (EROS)] and **Kevin Kephart** [SDSU] welcomed more than 80 participants to the three-day meeting. That attendance at such meetings continues to increase—likely due to the development of new data products and sensor systems—further highlights the growing interest in the Landsat program. The main objectives of this meeting were to provide a status update on Landsat 7 and 8, review team member research activities, and to begin identifying priorities for future Landsat missions. Meeting presentations are available at *http://landsat.usgs.gov/landsat-science-team-meeting-july-26-28-2016.php*.

Landsat 7 and 8 Status Update

Brian Sauer [USGS EROS—*Landsat Sustaining Engineering Project Manager*] offered an update on the mission status of Landsat 7 and 8. Sauer reported that Landsat 7's duty cycle has been raised to 105%, resulting in ~15 more scene acquisitions per day. On average, Landsat 7 is now acquiring around 470 scenes per day. The USGS is committed to continuity by extending Landsat 7's operational life until the launch of Landsat 9 late in 2020. Once retired, plans are being prepared to use Landsat 7 to test satellite-refueling technology via the NASA Restore-L mission.[1]

The in-orbit performance of Landsat 8 continues to be outstanding, currently acquiring around 740 scenes per day, and several Antarctic and Arctic off-nadir requests have recently been fulfilled with no impact on routine imaging. Operational and data processing solutions have been implemented to mitigate the impact of the anomaly in Landsat 8's Thermal Infrared Sensor (TIRS) scene select mirror (SSM)—see *Landsat 8 TIRS Stray Light Correction* on page 46 to learn more. All affected data have been reprocessed and nominal TIRS data collection and processing have been restored.

Landsat Global Archive Consolidation

Sauer also provided a brief update on the Landsat Global Archive Consolidation (LGAC) effort to repatriate data from international ground stations. He noted the that European Space Agency (ESA) is in the process of delivering to the USGS nearly two million scenes acquired between 1987 and 1999. Around 500,000 of these scenes contain no Payload Correction

[1] Scheduled for launch in 2020, the Restore-L mission uses a robotic spacecraft equipped with the tools, technologies, and techniques needed to extend satellites' lifespans—even if they were not designed to be serviced in orbit. To learn more please visit *https://sspd.gsfc.nasa.gov/restore-L.html*.

The Landsat Science Team.

Data (PCD),[2] so additional development is needed to improve image geometry. Data from Argentina are currently being added to the Landsat archive, with digital ingest expected to be completed by mid-2017.

New Landsat Products and Collections

Sauer also provided an update on the status of the new tiered collection management system being implemented at EROS. Although Landsat data will soon be organized using a three-tiered system (i.e., Near-Real Time, Tier 1, and Tier 2), it is important to note that all data, regardless of geometric or radiometric quality, will still be available to all users. Starting with Collection 1, Landsat 4-5 Thematic Mapper (TM), Landsat 7 Enhanced Thematic Mapper Plus (ETM+), and Landsat 8 Operational Land Imager (OLI)/Thermal Infrared Sensor (TIRS) scenes will be assigned to a specific tier. Several changes are being implemented to Landsat Level-1 data products to support this effort, including new Landsat Product Identifiers (a file naming convention), "Collection" and "Tier" designations, metadata changes, and the addition of new supporting files including a Quality Assurance (QA) band, Top of Atmosphere (TOA) angle coefficients, land-based cloud cover scores, and new life-long gain adjustments for TM sensors. TM and ETM+ data for the U.S. are being processed first, from newest to oldest, followed by U.S. OLI/TIRS data, and finally, the rest of the global archived data will be processed. Landsat Multispectral Scanner (MSS) data will be considered after processing for Landsat 7 and 8 are completed. At present, the goal is to finish processing Collection 1 by the end of May 2017. For more information on Landsat Collections, visit *http://landsat.usgs.gov/landsatcollections.php#collection*.

Landsat MSS Improvement Plan

Ron Morfitt [USGS EROS—*Landsat 8 Calibration and Validation Lead*] discussed efforts to improve the Landsat MSS archive, including MSS reflectance-based calibration, adjustment of minimum and maximum radiance values to minimize saturation, updating of gain-trend models, and derivation of a bulk correction factor to minimize attitude bias. Overall, the processing and model updates being implemented will help increase the number—as well as the geometric and radiometric quality—of MSS Level-1T scenes. Currently, the plan is to begin collection-processing for MSS in the summer of 2017.

Landsat 8 TIRS Reprocessing Status

Ron Morfitt also described how image measurements from geometric calibration are being used to correct the SSM issue, which caused TIRS images to be shifted out of alignment with OLI by as much as 500 m (~1640 ft). Overall, the new TIRS processing model is working well, with registration accuracy of around 20 m (~66 ft) when telemetry and calibration data are available.

Landsat 8 TIRS Stray Light Correction

Matt Montanaro and **Aaron Gerace** [both from Rochester Institute of Technology] provided an update on the stray-light correction algorithm being developed for TIRS on Landsat 8. Montanaro explained how stray light entering the optical path from outside the direct field-of-view is causing significant nonuniform banding in TIRS bands 10 and 11. The approach to correct this issue uses TIRS data to estimate the out-of-view signal, based on in-scene statistics. Initial validation results based on comparison with underpass data from the Moderate Resolution Imaging Spectroradiometer (MODIS) on Terra are encouraging. Although more testing is planned over land and low-temperature regions of Antarctica, the LST recommended moving toward operational implementation of the developed stray-light correction algorithm. The current plan is to implement the algorithm during Collection 1 reprocessing, which is slated to begin in the fall of 2016.

Landsat 9 Development Status

Del Jenstrom [NASA's Goddard Space Flight Center (GSFC)—*Landsat 9 Project Manager*] and **Jim Nelson** [USGS—*Landsat 9 Project Manager*] provided an update on the status of Landsat 9, which will be a full Class-B rebuild of Landsat 8. This approach minimizes risk and reduces reviews, which saves both time and money. TIRS2 is being upgraded to a Class B instrument, with additional steps being taken to fix the stray-light issue affecting the Landsat 8 TIRS instrument. As for previous missions, NASA is responsible for the space segment, including instrumentation and launch, and on-orbit checkout, while USGS will develop and manage the ground systems, including data collection, processing, archiving, and distribution. Level-1 science requirements have already been approved by both agencies, and everything is currently on track for a late-2020 launch date. Jenstrom noted that key lessons from the Landsat Data Continuity Mission (LDCM, now called Landsat 8) are being implemented at all project levels.

Landsat 10 Requirements and Capabilities Discussion

The LST initiated discussions that will lead to recommendations for capabilities for future Landsat missions. **Curtis Woodcock** [Boston University—*LST Co-Lead*] led a review and validation of the 2014 LST Landsat continuity statement.[3] The LST members confirmed that continuity was the primary driver of future missions. **Greg Snyder** [USGS Headquarters] reviewed

[2] Payload correction data contain attitude and ephemeris information needed to calculate (i.e., correct) the location of the pixels on the ground. Since the spacecraft moves and rotates somewhat rapidly, these data are needed at a high rate (once per second or more) to position the pixels within the 12 m (~39 ft) geolocation specification.

[3] To read the statement, visit *http://landsat.usgs.gov/documents/LST_Landsat_Continuity_Requirements.pdf*.

USGS's efforts to collect detailed user requirements related to future Landsat mission requirements. **Jeff Masek** [GSFC—*Landsat 9 Project Scientist*] reviewed the status of several technology investigations focused on reducing instrument size and weight. Masek also shared information and updates regarding a 2015 NASA Earth Science Technology Office solicitation for advanced technology demonstrations and long-term technology investment concepts. Awards for the 2015 Research Opportunities in Space and Earth Sciences (ROSES) solicitation were announced in August 2016.[4] **David Roy** [SDSU—*LST Co-Lead*] summarized LST member suggestions on new capabilities needed for Landsat 10 and beyond. Afterward, LST members discussed requirements and capabilities and defined five areas for more detailed study: continuity and backward compatibility with previous Landsat sensors, temporal frequency improvements, spatial and geometric improvements, radiometry resolution and signal-to-noise improvements, and new spectral measurements. Study teams will provide preliminary recommendations at the next LST meeting—see **Conclusion** for details.

[4] To view the announcements, visit *https://esto.nasa.gov/files/solicitations/SLIT_16/ROSES2015_SLIT_A47_awards.html*.

Landsat Science Team Member Presentations

The **Table** below summarizes the presentations given by members of the LST during the meeting. Please refer to the URL in the **Introduction** for more details on each presentation.

Table. Highlights from LST member presentations.

Presenter(s)	Affiliation	Highlights
John Kerekes	Rochester Institute of Technology (RIT)	Provided an overview of a test version of the Digital Imaging and Remote Sensing Generation (DIRSIG) model, a physics-based, scene-simulation tool for studying future Landsat systems.
Nima Pahlevan	NASA's Goddard Space Flight Center (GSFC)	Discussed the use of Landsat 8 and Sentinel 2A in aquatic science applications.
Anthony Vodacek	RIT	Showed how Landsat 8 is being used to monitor cyanobacteria in the U.S. Great Lakes region.
Yongwei Sheng	University of California Los Angeles	Described the use of Landsat 8 for mapping global lake presence and lake-level elevation.
Ted Scambos	University of Colorado	Discussed how more acquisitions and improved radiometric fidelity of Landsat 8 are helping to map ice flow speeds, surface roughness, and surface temperatures in Greenland and Antarctica.
Rick Allen	University of Idaho	Described the challenges and impacts of using Visible Infrared Imaging Radiometer Suite (VIIRS) and Moderate Resolution Imaging Spectroradiometer (MODIS) data to fill in gaps in Landsat evapotranspiration products.
Alan Belward	European Commission Joint Research Centre	Discussed the importance of the Landsat Global Archive Consolidation (LGAC) effort for producing next generation terrestrial essential climate variables.
Jim Vogelmann	USGS EROS	Showed how models fit to all available Landsat data are being used to assess changes in vegetation health.
Leo Lymburner, Adam Lewis	Geoscience Australia	Described Geoscience Australia's efforts to improve atmospheric correction, data integration with other sensors, and time series analysis including interpolation, modeling, and future projection of data.
David Roy	South Dakota State University (SDSU)	Presented a generalized, empirical line method for correcting bidirectional reflectance distribution function (BRDF) effects in Landsat images.
Crystal Schaaf	University of Massachusetts, Boston	Discussed production of a North American surface albedo product from Landsat data. Described ongoing validation of initial albedo maps of the Continental U.S.

Table. Highlights from LST member presentations. (cont)

Presenter(s)	Affiliation	Highlights
Joel McCorkel	GSFC	Presented an overview of the new modeling techniques and lasers being used to improve the sensor model for Landsat 9.
Eric Vermote	GSFC	Discussed the current status and performance of the Landsat 8 and Sentinel 2 surface reflectance algorithms. Results and future directions will be discussed at an upcoming, Landsat/ Sentinel 2 atmospheric correction workshop.
Dennis Helder	SDSU	Transferred Landsat 8 TOA alibration back in time to achieve a consistent, reflectance-based calibration of the whole Landsat archive. A summary of final gains and biases from Landsat 8 dating back to Landsat 1 is forthcoming.
Rick Lawrence	Montana State University	Presented an overview of research from the AmericaView group, including evaluation of Landsat 8 surface reflectance for modeling percent mortality from bark beetle outbreaks and mapping dissolved organic matter and chlorophyll concentrations in Minnesota.
Patrick Hostert	Humboldt University of Berlin	Discussed efforts to map forest dynamics in Southern Amazonia using Landsat time series. Focused on the use of temporal filters to develop coherent successional pathways and use of change metrics as classification inputs.
Txomin Hermosilla	Canadian Forest Service (CFS)	Described development of best pixel time series composites for mapping forest disturbance year, agent, and recovery times across Canada.
Mike Wulder	CFS	Showed how Landsat disturbance maps are being used to develop Canada-wide estimates of harvest and wildfire rates and recovery times. Also described a filtering approach to resolve successional transitions in annual land cover maps.
Joe Hughes (for Robert Kennedy)	Oregon State University	Discussed the challenges and opportunities of using Google Earth Engine to map land cover and cause of disturbance. Stressed the importance of quantifying uncertainty both spatially and numerically.
Randy Wynne	Virginia Polytechnic Institute and State University	Reviewed new algorithms and data fusion techniques to improve estimates of forest status and change. Demonstrated a Monte Carlo simulation approach to approximate prediction uncertainty for random forest regression models.
Warren Cohen	U.S. Department of Agriculture (USDA) Forest Service	Presented an approach for improving the radiometric and geometric quality of MSS and other Landsat Level-1G images for use in forest change applications.
Mark Friedl	Boston University	Discussed the use of Landsat data to study seasonal covariation in land surface climate and surface properties in the Boston metropolitan area. Described how the results suggest urban heat islands are one factor causing leaves to emerge earlier and senesce later in cities.
Curtis Woodcock	Boston University	Discussed the importance of using time series change metrics for classification and analysis. Showed how denser time series can lead to better quantification of subtle change events like gypsy moth outbreaks in the eastern U.S.
Feng Gao	USDA Agricultural Research Service	Presented an approach for mapping crop progress and yield at field scale with 30-m Landsat data.

Table. Highlights from LST member presentations. (cont)

Presenter(s)	Affiliation	Highlights
Martha Anderson, Yun Yange	USDA Agricultural Research Service (ARS)	Discussed the use of Landsat–MODIS data fusion techniques to improve daily evapotranspiration models.
Jim Hipple	USDA ARS	Presented an overview of the use of Landsat science products in the USDA ARS national agricultural data warehouse. Also discussed how Landsat data are being used to create mappable reports of crop loss.
Dave Johnson	USDA National Agricultural Statistics Service	Discussed the benefits of combining Sentinel 2A and Landsat data to estimate yields of winter wheat in Kansas.
Ayse Kilic	University of Nebraska	Showed how evapotranspiration time series can be used to estimate turf water conservation in California.

Landsat Advisory Team Update

Kass Green [*Kass Green & Associates*] summarized the activities of the Landsat Advisory Group (LAG), which is part of the Department of the Interior-sponsored National Geospatial Advisory Committee. The LAG is working to finalize a report summarizing feedback from non-federal Landsat users' requirements,[5] and make future recommendations on improving access and use of Sentinel-1 and -2 and data from other small-satellite sensors. Finally, at the request of USGS, the LAG is also updating their 2013 product improvement and cloud computing reports.

Landsat 8 Surface Reflectance Update

John Dwyer [USGS EROS—*Landsat Project Scientist*] provided an update on recent changes to the Landsat 8 surface reflectance algorithm, now referred to as Landsat Surface Reflectance Code (LaSRC) 3.0. Released on June 23, 2016, the updates include use of blue and red bands (instead of deep blue and red) for improved, ratio-based aerosol inversion performance. The previously reported issues of spatial blockiness,[6] particularly around offshore coastal regions, has been resolved by applying the aerosol interpolation at the 30-m pixel level (versus the coarser 0.05° Climate Modeling Grid (CMG) level), and by dropping the land/water mask. Future plans involve conducting a more thorough comparison of Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) and Landsat Surface Reflectance Code (LaSRC) reflectance retrievals, so that compatibility and differences can be documented and shared with users. Dwyer stressed the importance of this information, as users need to know more about how surface reflectance products from different Landsat sensors relate to one another.

[5] Increasing Landsat's temporal acquisition frequency is by far the most requested improvement cited by non-federal users.
[6] Spatial blockiness refers to multi-pixel checker-board patterns resulting from using coarse resolution inputs to atmospherically correct 30-m Landsat pixels.

USGS Land Change Monitoring, Assessment and Projection Update

Tom Loveland discussed the ongoing evolution of the USGS Land Change Monitoring, Assessment and Projection (LCMAP) project. Designed as a modernized, integrated approach to mapping, monitoring, and synthesizing land-use and land-cover change information, LCMAP will use Landsat Analysis Ready Data (ARD) as the foundation to provide a capability to continuously map and monitor changes in land cover across the U.S. **Brian Sauer** provided an update on the status of ARD implementation. The goal is to prioritize the availability of stable and consistent TOA, surface reflectance, and brightness temperature products, thereby enabling users to directly interact with the highest-quality Landsat data with minimal need for preprocessing. ARD data will be generated using Collection 1 inputs, so that changes and updates have a clearly traceable provenance. The plan is to first process data for TM/ETM+/OLI over the U.S., then expand globally—including the addition of MSS data. **Zhe Zhu** [ASRC Federal InuTeq, a USGS contractor] gave an update on ongoing efforts to fine tune the Continuous Change Detection and Classification (CCDC) algorithm to produce annual land-cover and land-cover change maps operationally using Landsat ARD inputs.

South Dakota State University Remote Sensing Activities

Meeting co-hosts **David Roy** and **Dennis Helder** [SDSU—*LST member*] and their colleagues made several presentations showcasing a number of ongoing SDSU research projects that were of interest to the LST. The presentations covered a wide range of topics including: the use of Landsat time series to detect ecological thresholds in West African tropical forests, synergistic use of Landsat and MODIS data to characterize land-surface phenologies in Kyrgyzstan, development of Landsat 8 and Sentinel 2 burned-area products, detecting new pseudo-invariant calibration sites for vicarious calibration of Landsat and other optical sensors, use of Landsat time series to assess vulnerability and response of fragmented forests in the Amazon, and quantification of time series inconsistencies caused by satellite orbital drift.

Conclusion

The 2016 summer LST meeting focused on identifying a number of important priorities to improve several aspects of the Landsat program. LST members offered guidance and recommendations on developing new Landsat products, enhanced synergy with Sentinel-2, and improving the MSS data record. The wide range of science and applications talks given by the LST members highlighted the increased capacity and ambition that may be brought to analyses based upon free and open data, available in an analysis-ready form. The firm cross-governmental support of the Landsat program has empowered the science community while also engendering agency support through an expectation of future access to an uninterrupted and high-quality Earth-observation data stream. The repeated highlighting of the importance of continuity of Landsat measures came from all user communities present or represented at the meeting. With reference to continuity, following initial context setting, team discussions led to identifying key steps toward informing what will become Landsat 10. The discussions regarding Landsat 10 identified a need to determine opportunities to take advantage of new technologies, clearly stressing the importance of measurement continuity across sensors across the Landsat program.

The next LST meeting will be held January 10-12, 2017, at Boston University in Boston, MA. ■

Congratulations William T. Pecora Award Winners

The Earth Observer is pleased to recognize the entire **Tropical Rainfall Measuring Mission (TRMM) Team** and **Curtis Woodcock** [Boston University—*Landsat Science Team Lead*] for receiving the 2016 *William T. Pecora* Team Award and Individual Award, respectively.

For more than 17 years, the **TRMM Team** has conducted innovative precipitation science and has developed widely used applications that have greatly benefitted society. The mission was launched in late 1997 and ended in 2015, and was a joint endeavor between NASA and the Japan Aerospace Exploration Agency (JAXA). The TRMM team met and exceeded their original goal of advancing our understanding of the distribution of tropical rainfall and its relation to the global water and energy cycles. As of May 2016, more than 2700 publications have TRMM in their title according to Google Scholar, and there are more than 25,000 citations of these TRMM papers. By their outstanding efforts, the TRMM team has advanced precipitation science and paved the way for the next generation of precipitation observations.

Curtis Woodcock, a professor at Boston University, has dedicated his career to remote sensing education, research, and service. After joining Boston University in 1984, he co-founded the Center for Remote Sensing and served as chair of the Department of Geography for 13 years. Woodcock has led the Landsat Science Team for nearly 10 years. He has played a key role in opening and expanding the Landsat archive, and he has provided guidance for the USGS initiative to modernize Landsat-scale global land monitoring. His seminal work on scaling and geostatistics continues to influence the way we understand remotely sensed imagery, and his work on land-cover mapping “best practices” unified a scattered academic community. His research over more than 30 years has effectively changed our basic understanding of remote sensing science.

The *William T. Pecora Award* was established in 1974 to honor the memory of William T. Pecora, former Director of the U.S. Geological Survey (USGS) and Undersecretary of the Department of Interior (DoI). Pecora was a motivating force behind the establishment of a program for civil remote sensing of Earth from space. His early vision and support helped establish what we know today as the Landsat satellite program, which created a continuous record of Earth’s land areas that has now spanned a period of more than 40 years.

The award is sponsored by DoI’s USGS and NASA, and presented annually to individuals and/or groups that make outstanding contributions toward understanding Earth by means of remote sensing. This year’s award was presented on September 21 at a special commemorative event, *A Vision to Observe Earth … 50th Anniversary*, held in Washington, DC.

To learn more about this award and this year’s group and individual winners please visit *http://remotesensing.usgs.gov/pecora.php*.

New, Space-Based View of Human-Made Carbon Dioxide

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Carol Rasmussen, NAS'sA Earth Science News Team, carol.m.rasmussen@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.

Scientists have produced the first global maps of human emissions of carbon dioxide (CO_2) ever, made solely from satellite observations of the greenhouse gas. The maps, based on data from NASA's second Orbiting Carbon Observatory-2 (OCO-2) satellite and generated with a new data-processing technique, agree well with inventories of known CO_2 emissions.

No satellite before OCO-2 was capable of measuring CO_2 in fine enough detail to allow researchers to create maps of human emissions from the satellite data alone. Instead, earlier maps also incorporated estimates from economic data and modeling results.

The team of scientists from the Finnish Meteorological Institute (FMI), Helsinki, produced three main maps from OCO-2 data, each centered on one of Earth's highest-emitting regions: the eastern U.S., central Europe (see **Figure**), and east Asia. The maps show widespread CO_2 across major urban areas and smaller pockets of high emissions.

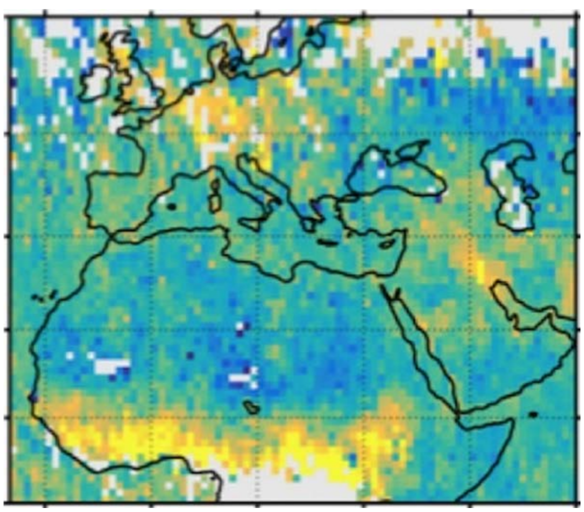

Figure. Human carbon dioxide (CO_2) emissions over Europe, the Middle East, and northern Africa. Values range from 3 parts per million CO_2 below background levels (navy blue) to 3 parts per million above (pale yellow). High emissions over Germany and Poland [*top center*] and Kuwait and Iraq [*right*] mostly come from fossil fuel burning, but over sub-Saharan Africa they mostly come from fires. **Image credit:** FMI

"OCO-2 can even detect smaller, isolated emitting areas like individual cities," said **Janne Hakkarainen** [FMI—*Research Scientist*] who led the study. "It's a very powerful tool that gives new insight."

The results appear in a paper titled "Direct Space-Based Observations of Anthropogenic CO_2 Emission Areas from OCO-2," published November 1 in the journal *Geophysical Research Letters*.

Human emissions of CO_2 have grown at a significant rate since the Industrial Revolution, and the greenhouse gas lingers in the atmosphere for a century or more. This means that recent human output is only a tiny part of the total CO_2 that OCO-2 records as it looks down toward Earth's surface. "Currently, the background level of CO_2 in the atmosphere is about 400 parts per million, and human emissions within the past year may add only something like three parts per million to that total," said Hakkarainen. The data-processing challenge, he noted, was to isolate the signature of the recent emissions from the total amount.

The team's new data-processing technique accounts for seasonal changes in CO_2, the result of plant growth and dormancy, as well as the background CO_2 level. To be sure their method was correct, they compared the results with measurements of nitrogen dioxide (NO_2)—another gas emitted from fossil fuel combustion—from the Ozone Monitoring Instrument, a Dutch–Finnish instrument on NASA's Aura satellite. OMI and OCO-2 are both in the A-Train satellite constellation, so the two measurements cover the same area of Earth and are separated in time by only 15 minutes.

The two measurements correlated well, giving the researchers confidence that their new technique produced reliable results.

Coauthor **Johanna Tamminen** [FMI—*Head of the Atmospheric Remote Sensing Group*] noted that with its comparison of OCO-2 and OMI data, "The research demonstrates the possibility of analyzing joint satellite observations of CO_2 and other gases related to combustion processes to draw out information about the emissions sources."

Annmarie Eldering [NASA/Jet Propulsion Laboratory—*OCO-2 Deputy Project Scientist*] said, "We are very pleased to see this research group make use of the OCO-2 data. Their analysis is a great demonstration of discovery with this new dataset." Eldering was not involved in the study. ■

See How Arctic Sea Ice Is Losing Its Bulwark Against Warming Summers

Maria José Viñas, NASA's Goddard Space Flight Center, maria-jose.vinasgarcia@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.

Arctic sea ice, the vast sheath of frozen seawater floating on the Arctic Ocean and its neighboring seas, has been hit with a double whammy over the past decades: as its extent shrunk, the oldest and thickest ice has either thinned or melted away, leaving the sea ice cap more vulnerable to the warming ocean and atmosphere.

"What we've seen over the years is that the older ice is disappearing," said **Walt Meier** [NASA's Goddard Space Flight Center—*Sea Ice Researcher*]. "This older, thicker ice is like the bulwark of sea ice: a warm summer will melt all the young, thin ice away but it can't completely get rid of the older ice. But this older ice is becoming weaker because there's less of it and the remaining old ice is more broken up and thinner, so that bulwark is not as good as it used to be."

Direct measurements of sea ice thickness are sporadic and incomplete across the Arctic, so scientists have developed estimates of sea ice age and tracked their evolution from 1984 to the present—see **Figure**. A new

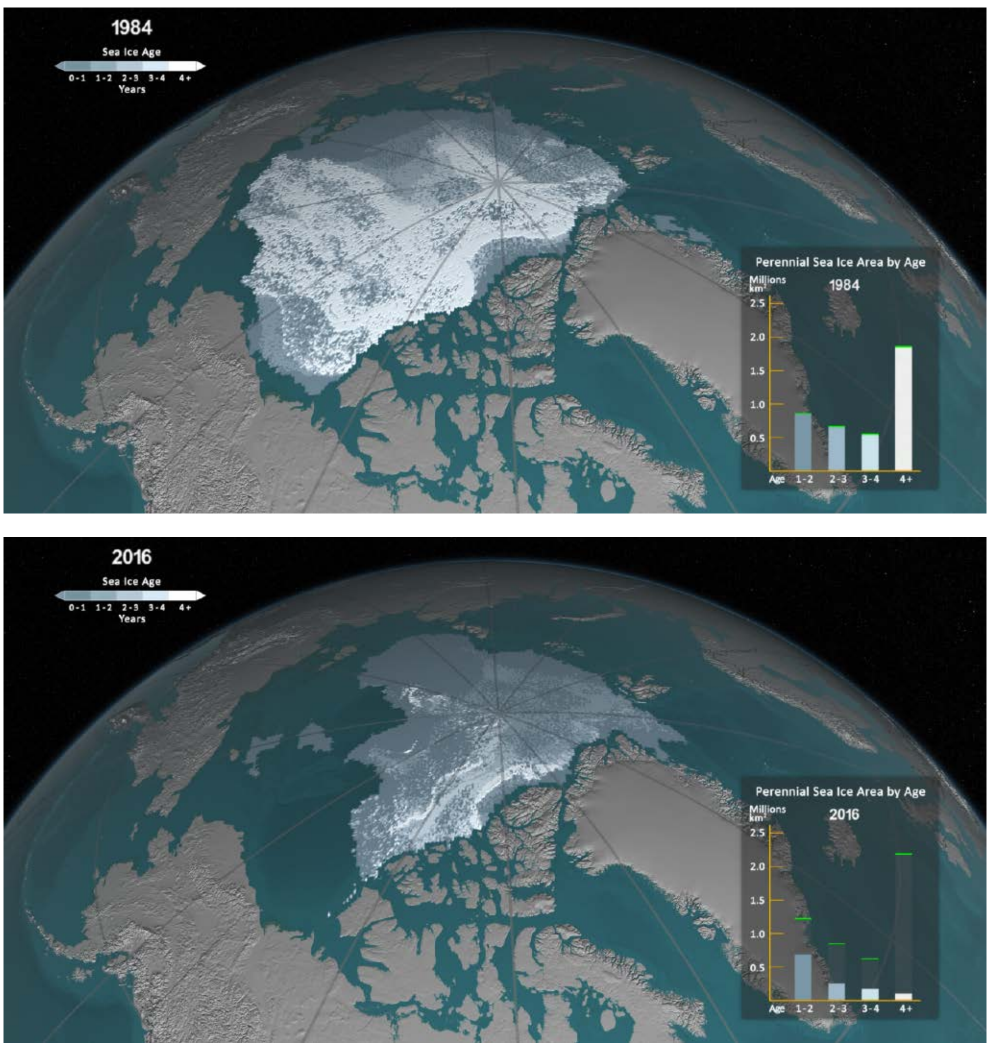

Figure. These images show the extent of older sea ice in the Arctic in September 1984 [*top*] and September 2016 [*bottom*]. The older ice is thicker and more resistant to melt than new ice, so it protects the sea ice cap during warm summers. In September 1984, there were 1.86 million km^2 (~718,000 mi^2) of old ice (ice that is 5 years old or older) left throughout the Arctic sea ice cap during its yearly minimum extent; in September 2016, there were only 110,000 km^2 (42,000 mi^2) of older sea ice left. **Image credit:** NASA's Scientific Visualization Studio

NASA visualization[1] of the age of Arctic sea ice shows how sea ice has been growing and shrinking, spinning, melting in place, and drifting out of the Arctic for the past three decades.

"Ice age is a good analog for ice thickness because basically, as ice gets older it gets thicker," Meier said. "This is due to the ice generally growing more in the winter than it melts in the summer."

In the early 2000s, scientists at the University of Colorado developed a way to monitor Arctic sea ice movement and the evolution of its age by using data from a variety of sources—but primarily from satellite passive microwave instruments. These instruments gauge *brightness temperature*: a measure of the microwave energy emitted by sea ice that is influenced by the ice's temperature, salinity, surface texture, and the layer of snow on top of the sea ice. Each floe of sea ice has a characteristic brightness temperature, so the researchers developed an approach that would identify and track ice floes in successive passive microwave images as they moved across the Arctic. The system also uses information from drifting buoys as well as weather data.

"It's like bookkeeping; we're keeping track of sea ice as it moves around, up until it melts in place or leaves the Arctic," said Meier, who is a collaborator of the group at the University of Colorado and the National Snow and Ice Data Center, the center that currently maintains the Arctic sea ice age data.

Ice in motion

Every year, sea ice forms in the winter and melts in the summer. The sea ice that survives the melt season thickens with each passing year: newly formed ice grows to about 3-7 ft (~1-2 m) of thickness during its first year, while *multi-year ice* (sea ice that has survived several melt seasons) is about 10-13 ft (~3-4 m) thick. The older and thicker ice is more resistant to melt and less likely to get pushed around by winds or broken up by waves or storms.

[1] To watch the visualization, visit *http://www.nasa.gov/feature/goddard/2016/arctic-sea-ice-is-losing-its-bulwark-against-warming-summers*.

Arctic sea ice has not only been shrinking in surface area in recent years, it's becoming younger and thinner as well. In the visualization mentioned earlier, where the ice cover almost looks gelatinous as it pulses through the seasons, Meier describes how the sea ice has undergone fundamental changes during the era of satellite measurements.

"On a week-to-week basis, there are weather systems that come through, so the ice isn't moving at a constant rate: sometimes the Beaufort Gyre reverses or breaks down for a couple weeks or so, the Transpolar Drift Stream shifts in its direction…but the overall pattern is this one," Meier said. "Then the spring melt starts and the ice shrinks back, disappearing from the peripheral seas."

The animation shows two main bursts of thick ice loss: the first one, starting in 1989 and lasting a few years, was due to a switch in the Arctic Oscillation, an atmospheric circulation pattern, which shrunk the Beaufort Gyre and enhanced the Transpolar Drift Stream, flushing more sea ice than usual out of the Arctic. The second peak in ice loss started in the mid-2000s.

"Unlike in the 1980s, it's not so much as ice being flushed out—though that's still going on too," Meier said. "What's happening now more is that the old ice is melting within the Arctic Ocean during the summertime. One of the reasons is that the multiyear ice used to be a pretty consolidated ice pack and now we're seeing relatively smaller chunks of old ice interspersed with younger ice. These isolated floes of thicker ice are much easier to melt."

"We've lost most of the older ice: In the 1980s, multiyear ice made up 20% of the sea ice cover. Now it's only about 3%," Meier said. "The older ice was like the insurance policy of the Arctic sea ice pack: as we lose it, the likelihood for a largely ice-free summer in the Arctic increases." ■

2016 Antarctic Ozone Hole Attains Moderate Size, Consistent With Scientific Expectations

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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 hole in Earth's ozone layer that forms over Antarctica each September[1] grew to about 8.9 million mi^2 (~23 million km^2) in 2016 before starting to recover, according to scientists from NASA and the National Oceanic and Atmospheric Administration (NOAA) who monitor the annual phenomenon**.**

"This year we saw an ozone hole that was just below average size," said **Paul Newman** [NASA's Goddard Space Flight Center—*Chief Scientist for Atmospheric Sciences*]. "What we're seeing is consistent with our expectation and our understanding of ozone depletion chemistry and stratospheric weather."

At its peak on September 28, 2016, the ozone hole extended across an area nearly three times the size of the continental U.S. The average area of the hole observed since 1991 has been roughly 10 million mi^2 (~26 million km^2). In 2015, the ozone hole grew to 10.9 million mi^2 (~28 million km^2), 2 million mi^2 (~5.2 million km^2) larger than this year, before returning to relatively normal summer levels. Its larger size last year was due to colder-than-average temperatures in the stratosphere that amplified the destruction of ozone by sunlight reacting with chlorine and bromine from man-made chemicals, scientists said. In 2016, warmer stratospheric temperatures constrained the growth of the ozone hole.

Ozone, which occurs naturally in small amounts in the atmosphere, is comprised of three oxygen atoms as opposed to the two that make up the much more abundant molecular oxygen. High in the stratosphere, ~6 to 30 mi (~10 to 48 km) above the surface, the ozone layer acts like sunscreen, shielding Earth from potentially harmful ultraviolet radiation that can cause skin cancer, cataracts, and suppress immune systems, as well as damage plants. Ozone is also one of the primary greenhouse gasses that regulate Earth's temperature.

First detected in 1985, the Antarctic ozone hole forms during the Southern Hemisphere's late winter months of August and September as the sun's rays return after months of polar night. The sunlight initiates catalytic reactions that produce chemically active forms of chlorine and bromine concentrated over the South Pole during winter. These reactions rapidly destroy ozone molecules.

In addition to the area of the ozone hole, scientists also measure the concentration of ozone that would be found in a column of atmosphere extending from the surface to the edge of space. The most common unit for measuring ozone concentration is the Dobson Unit (DU), which is the number of ozone molecules that would be required to create a layer of pure ozone 0.01 mm thick at a temperature of 32 °F (0 °C) at an atmospheric pressure equivalent to Earth's surface.

This year, the ozone layer reached a minimum concentration of 114 Dobson Units on October 1, 2016. In 2015, the ozone layer reached a minimum of 101 DU on October 4. During the 1960s, before the Antarctic ozone hole occurred, average ozone concentrations above the South Pole ranged from 260 to 320 DU—see **Figure**.

This year's Antarctic ozone hole is similar to the 2013 hole, which reached 9.3 million mi^2 (24 million km^2). Although warmer than average stratospheric weather conditions reduce ozone depletion, the current ozone hole area is large compared to the 1980s, when the depletion of the ozone layer above Antarctica was first detected. This is because levels of ozone-depleting substances remain high enough to produce significant ozone loss.

NASA and NOAA monitor ozone levels via three complementary instrumental methods. NASA's Aura satellite and the NASA-NOAA Suomi National Polar-orbiting Partnership satellite measure ozone from space. The Aura satellite's Microwave Limb Sounder data are used to estimate chlorine levels.

NOAA scientists monitor the thickness of the ozone layer and its vertical distribution above at the South Pole station by regularly releasing weather balloons carrying ozone-measuring "sondes" and with a ground-based instrument called a Dobson spectrophotometer.

[1] An animation describing how the 2016 Antarctic ozone hole evolved as scientists expected and placing it in the larger context of the annual phenomenon can be found at *http://www.nasa.gov/feature/Goddard/2016/antarctic-ozone-hole-attains-moderate-size*. An animation showing the size and shape of the ozone hole each year from 1979 through 2016 (no data are available for 1995) can be viewed at *http://www.earthobservatory.nasa.gov/Features/WorldOfChange/ozone.php*. This URL also contains more descriptive information.

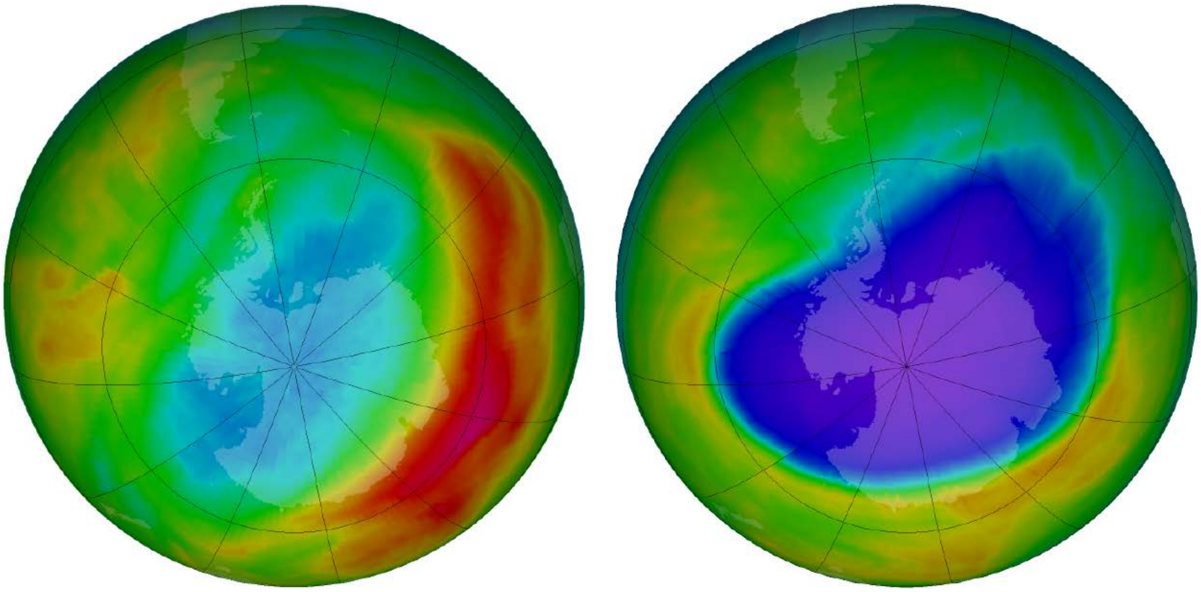


Figure. Prior to 1979, scientists had not observed total ozone amounts below 220 DU. The *ozone hole*, a large, ozone depleted layer of the Antarctic lower stratosphere, reached its lowest concentration over Antarctica of 194 DU on September 30, 1979 [*left*]. In the 1980's, the minimums became deeper rapidly: 173 DU in 1982, 154 DU in 1983, and 124 DU in 1985. This year [*right*], the ozone layer reached a minimum concentration of 114 DU on October 1, 2016. **Image credit**: NASA's Goddard Space Flight Center

"Our weather balloon measurements showed that the ozone minimum was a bit less and the rate of ozone loss a bit slower than we've typically seen," said **Bryan Johnson** [NOAA—*Atmospheric Chemist*]. "This is what we would expect to see in years to come as a result of the Montreal Protocol and international efforts to control ozone depleting chemicals."

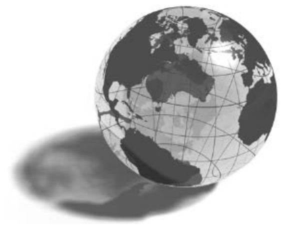
In 1987, the Montreal Protocol on Substances that Deplete the Ozone Layer began regulating ozone-depleting compounds, which are slowly declining. Scientists expect the ozone hole to recover back to 1980 levels around 2070. ■

New Harmonized Landsat–Sentinel Reflectance Product Available

The NASA–USGS Landsat mission and European Space Agency's Sentinel-2 missions have collaborated to produce a Harmonized Surface Reflectance Product. The data products from these missions represent the most widely accessible medium-to-high spatial resolution multispectral satellite data in the world. Following the recent launch of the first of two Sentinel-2 satellites, the potential for synergistic use of the two sources creates unprecedented opportunities for timely and accurate observation of Earth status and dynamics. Thus, harmonization of the distributed data products is of paramount importance for the scientific community. Activities to harmonize data products are on their way, yet more coordination is needed to allow the majority of users to easily and effectively include both data types into their work. To learn more, visit *http://hls.gsfc.nasa.gov*.

Landsat 8

Sentinel-2



NASA Earth Science in the News

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

La Niña Has Officially Arrived—And It's Bad News For The Drought-Parched West, November 10, *buzzfeed.com*. La Niña has officially arrived, but it may turn out to be more of a "La Nada," with little impact on the brutal multiyear drought in California and other western states. The National Oceanic and Atmospheric Administration (NOAA) declared Thursday, November 10, that La Niña conditions had begun, meaning the water in the equatorial Pacific Ocean is cooler than normal. This year's La Niña is expected to be weak and short-lived, "possibly only lasting a few months," said NOAA in a statement. **Mike Halpert** [NOAA's Climate Prediction Center—*Deputy Director*] said that the odds favor La Niña continuing through the rest of 2016, then decreasing during the early months of 2017. Also, the phenomenon is so weak it could ultimately just fizzle. **Bill Patzert** [NASA/Jet Propulsion Laboratory (JPL)—*Climatologist*] told BuzzFeed News the La Niña will be "almost a La Nada" and "barely visible in contrast to the fall of 1998."

*__NASA's Space-Based Maps of Carbon Dioxide Emissions__, November 10, *cosmosmagazine.com*. Carbon dioxide (CO_2) emissions have been mapped in high resolution by NASA's Orbiting Carbon Observatory-2 (OCO-2) satellite, showing widespread CO_2 across major urban areas, and smaller pockets of high emissions emanating from individual cities. In *Geophysical Research Letters*, a trio from the Finnish Meteorological Institute in Helsinki provides the first direct observation of anthropogenic CO_2 from OCO-2 over three main regions: eastern U.S., central Europe, and East Asia. Launched in 2014, OCO-2's path covers most of the globe every 16 days. It tracks CO_2 by measuring sunlight bouncing off the planet's surface. As the light filters through the atmosphere, CO_2 molecules absorb some of the infrared light, and OCO-2 detects these infrared differences.

NASA to Launch 'Swarms' of Small, Earth-Observing Satellites, November 8, *space.com*. NASA plans to launch a suite of tiny, next-generation satellites into Earth orbit to study weather patterns and climate change. These missions will conduct important scientific research while also advancing the technology needed to launch smaller, cheaper satellites, NASA said. The space agency hosted a teleconference on November 7, 2016, from its headquarters in Washington, DC, to discuss some of the new small satellites, or "smallsats," that will launch in the coming months. **Ellen Stofan** [NASA Headquarters—*Chief Scientist*] explained that small satellites can reduce the costs of space-based Earth observations. Additionally, the satellites can increase access to space for private companies as well as universities and students interested in pursuing science experiments in Earth orbit, Stofan said.

*__Watch as Old Sea Ice Vanishes,__ November 2, *cnn.com*. From year to year, the ice around the Arctic ebbs and flows, reaching a minimum and maximum as the temperature shifts through the seasons. Scientists recently released a time-lapse animation comparing Arctic sea ice extent since 1984 with present-day values, and what is shown is more than a little startling. The old sea ice—the Arctic sea ice that lasts year after year—is smaller than it has been in three decades. Lately the thinner, younger sea ice—less than a year old—has become the majority type across the Arctic. Young ice struggles to reach 2 m (~6.5 ft) thick during winter months and then is more likely to melt during the summer. In September 2016 Arctic sea ice shrank to the second-lowest level since data began being recorded in 1979. The polar sea ice has a direct influence on ocean circulation, weather, and regional climate around the globe. Vanishing sea ice is an easily interpreted indicator that climate change is taking place. According to NASA, many global climate models predict that the Arctic will be ice-free for at least part of the year before the end of the twenty-first century, and some models predict an ice-free Arctic by midcentury. If this holds true, it would have a direct impact on weather patterns seen globally.

These Antarctic Glaciers Have Experienced Staggering Ice Loss and Scientists Think They Know Why, October 25, *washingtonpost.com*. Few regions of the world are as unstable in the face of advancing climate change as frozen West Antarctica, where rapidly melting glaciers have scientists on edge about the potential for their causing huge amounts of future sea-level rise. Now, a new study has pinpointed some of the most rapid ice losses observed in the region in the past 15 years—and it supports a growing scientific belief that warm ocean water is behind the melting. "[The study] seems to provide a strong piece of evidence to support a general hypothesis about what's happening in the Amundsen Sea," said polar scientist **Ala Khazendar**, [JPL] and the new paper's lead author. Research increasingly suggests it's not just atmospheric warming that's causing all the problems in West Antarctica, but the influence of the ocean, as well. Many glaciers in this region back right up to the edge of the sea, terminating in what's known as an *ice shelf*—a ledge of floating ice that's disconnected from the bedrock and juts out into the water, helping to stabilize the glacier and hold back the flow of ice behind it. Scientists now believe that rising water temperatures may be helping to weaken ice shelves by seeping into the cavities beneath them and lapping up against the exposed ice.

Earth's Streak of Record Warm Months is Coming to a Temporary End, October 18, *mashable.com*. The planet is temporarily ending its streak of record warm global monthly temperatures, according to data released Tuesday, October 18, by NOAA as well as other figures, and recently published by NASA. However, given the increasing influence of long-term global warming, such streaks—including even longer ones than what just occurred—are becoming more likely with time. According to NOAA, September was the second warmest such month on record, with global average surface temperatures coming in at 0.89 °C (1.60 °F) above average for the month. This means September 2016 was 0.03 °C (0.07 °F) cooler than September of last year. This ranking ends the record-breaking streak of record warm months (yes, even the streak broke a record) at 16.

*See news story in this issue.

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****.*

Addressing Environmental Issues in America's National Parks: A Collaboration Between NASA DEVELOP and the National Park Service

continued from page 21

The Earth Observer would like to acknowledge the contributions to the efforts described here by the following individuals and groups:

Don Weeks [NPS, Intermountain Regional Office—*Physical Resources Program Manager*]

Kenton Ross [NASA, DEVELOP National Program Office—*National Science Advisor*]

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DEVELOP Goddard's Northern Great Plains Ecological Forecasting Team – Amanda Clayton, Jessica Fayne, Carl Green, Jared Tomlin

DEVELOP Idaho's Eastern Idaho Disasters Team – Courtney Ohr, Priscilla Addison, Jenna Williams

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DEVELOP Marshall's Chaco Canyon Cross-Cutting Team – Kelsey Herndon, Dashielle Cruz, Sydney Neeley, Ryan Schick

DEVELOP Wise County's Northern Great Plains Water Resources Team – Anne Gale, Michael Brooke, Xin Hong, Cody Vineyard.

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.

Our Magnificent Sun

Grade Level: K-8

What is the sun? What are sunspots?

Our Magnificent Sun for kindergarten through second grade, and upper elementary and middle school students will help answer questions about the sun in a highly interactive session.

The upcoming solar eclipse of 2017 provides a teachable moment, and *Our Magnificent Sun* introduces space weather and answers questions about solar eclipses. For more information, visit *http://www.nasa.gov/dln/lessons#Our%20Magnificent%20Sun*.

Free Program—Cubes in Space™

Program Registration Deadline: January 6, 2017

Cubes in Space™ provides students ages 11-18 an opportunity to design and compete to launch an experiment into space at no cost! This global education program based on science, technology, engineering, arts, and mathematics (STEAM) enables students to learn about space exploration using innovative problem-solving and inquiry-based learning methods. Cubes in Space™ is offered by *idoodledu, inc.*, in partnership with NASA's Goddard Space Flight Center's Wallops Flight Facility, the Colorado Space Grant Consortium, and NASA's Langley Research Center.

This year, experiments will be launched into space via sounding rocket from NASA's Wallops Flight Facility on Wallops Island, VA, in late June 2017 or from a high-altitude balloon launched from NASA's Columbia Scientific Balloon Facility in Fort Sumner, NM, in August 2017.

For more information, visit *http://www.cubesinspace.com*. Questions about this program may be directed to *info@cubesinspace.com*.

National Science Foundation's 2016-2017 Community College Innovation Challenge

Submission Deadline: February 15, 2017

The National Science Foundation's Community College Innovation Challenge is seeking proposals for innovative STEM-based solutions for real-world problems. Responding teams must include community college students, a faculty mentor, and a community or industry partner.

Challenge entries consist of a written portion and a 90-second video. Each team's entry must address one of this year's three themes: Maker to Manufacturer, Energy and Environment, and Security Technologies.

For additional information about the challenge, visit *https://www.nsf.gov/news/special_reports/communitycollege/index.jsp*.

Questions about this challenge should be directed to *InnovationChallenge@nsf.gov*.

2017-2018 Virginia Space Grant Consortium STEM Bridge Scholarships

Submission Deadline: March 13, 2017

The Virginia Space Grant Consortium is offering renewable $1000 scholarships to undergraduate students studying science, technology, engineering, or mathematics (STEM). The program encourages students to explore how their majors can apply to NASA's mission. The competitive scholarships are available to students who are U.S. citizens from any federally recognized minority group and are enrolled full time at one of the five Virginia Space Grant Consortium (VSGC) member universities. Applicants must have completed at least one year of a STEM undergraduate program and be classified as a sophomore during the 2017-2018 academic year.

For more information, visit *http://vsgc.odu.edu/sf/Bridge*.

The following announcements appeared in earlier issues of The Earth Observer, but still apply.

Subscribe to the NASA Education 'Science WOW!' Weekly Newsletter

To be added to the distribution list, register your email address at *http://www.nasa.gov/education/sciencewow*.

NASA Announcement for High Impact/Broad Implementation STEM Education Partnerships Still Open

For more information about this opportunity, visit NSPIRES at *http://go.nasa.gov/1RZwWCi*. Responses must be submitted electronically at *http://nspires.nasaprs.com*.

Searchable Portals for Federally Sponsored Opportunities for STEM Undergraduate and Graduate Students

Visit *http://stemundergrads.science.gov* for undergraduate programs and opportunities, and *http://stemgradstudents.science.gov* for graduate students. ■

EOS Science Calendar

January 10–12, 2017
Landsat Science Team Meeting,
Boston, MA.
http://landsat.usgs.gov/science_LST_Team_Meetings.php

January 11–13, 2017
ESIP Winter Meeting,
Bethesda, MD.
http://meetings.esipfed.org/winter-meeting-2017

January 31, 2017–February 2, 2017
SMAP Science Team Meeting,
Pasadena, CA.
http://smap.jpl.nasa.gov/events/49

April 12–13, 2017
LCLUC Spring Science Team Meeting,
Rockville, MD.
http://lcluc.umd.edu/meetings/2017-lcluc-spring-science-team-meeting-apr-12th-13th-and-musli-meeting-april-14th

April 17-18, 2017
AIRS Science Team Meeting, Pasadena, CA
http://airs.jpl.nasa.gov/events

Global Change Calendar

December 12–16, 2016
American Geophysical Union Fall Meeting,
San Francisco, CA.
http://fallmeeting.agu.org/2016

January 24–26, 2017
American Meteorological Society Annual Meeting,
Seattle, WA.
https://annual.ametsoc.org/2017

April 18–21, 2017
A-Train Symposium, Pasadena, CA.
https://espo.nasa.gov/a-train_2017/content/A-Train_2017

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

Undefined Acronyms Used in Editorial and Table of Contents

AGU	American Geophysical Union
CATS	Cloud-Aerosol Transport System
EOS	Earth Observing System
ESA	European Space Agency
GFZ	Geoforschungszentrum [German Research Center for Geosciences]
GOES	Geostationary Operational Environmental Satellite
GPS	Global Positioning Satellite
GSFC	NASA's Goddard Space Flight Center
GSOC	German Space Operations Center
GRACE	Gravity Recovery and Climate Experiment
IAGB	Industrieanlagen-Betriebsgesellschaft
JPL	NASA/Jet Propulsion Laboratory
LIS	Lightning Image Sensor
MSFC	NASA's Marshall Space Flight Center
NESDIS	National Environmental Satellite, Data, and Information Service
NOAA	National Oceanic and Atmospheric Administration
OMI	Ozone Monitoring Instrument
QuikSCAT	Quick Scatterometer
SAGE III	Stratospheric Aerosol and Gas Experiment III
UT/CSR	University of Texas/Center for Space Research

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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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