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Editor's Corner

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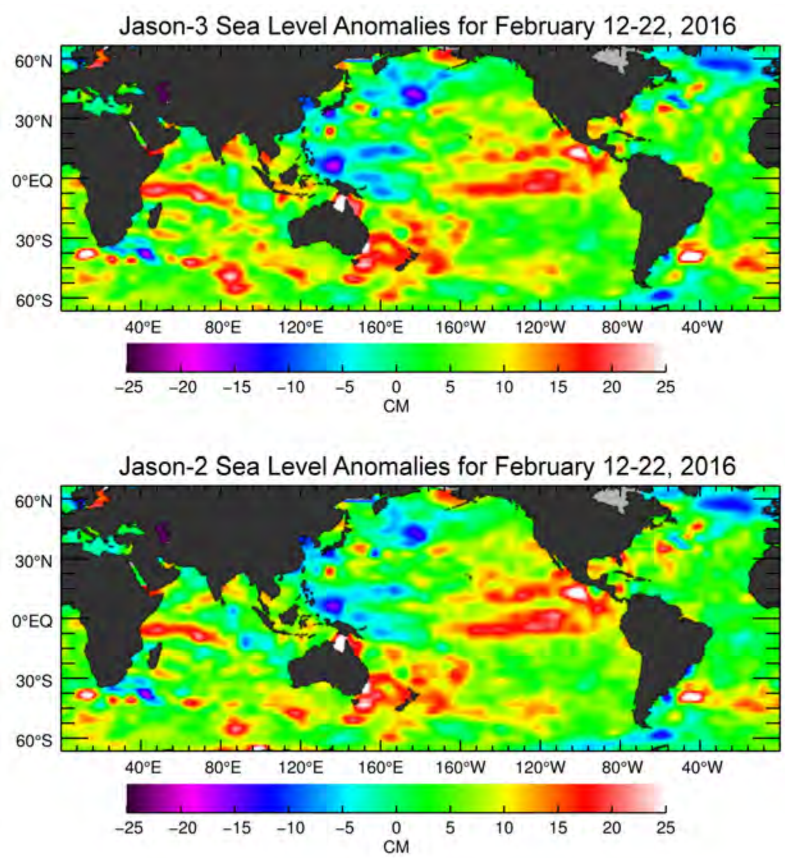
NASA's current satellite fleet includes 20 Earth-observing missions (see **Figure 1** on page 4 of this issue). While each satellite performs independent mission work, some augment their science capabilities by flying in close, coordinated proximity to one another as part of a *constellation*—e.g., the Afternoon Constellation, or "A-Train." Maintaining the orbits of each of these missions and keeping them all safely operating presents daily challenges. On page 4 of this issue, we provide an overview of NASA's Earth Science Mission Operations (ESMO) Project. In particular, the article focuses on ESMO's Flight Operations Segment (FOS), which is responsible for flight operations for six missions—Terra, Aqua, Aura, the GPM Core Observatory, EO-1, and SORCE. ESMO assumes responsibility for operation of a given mission following successful launch and early-orbit activities, and their involvement continues through a mission's lifetime, including the eventual deactivation phase. In addition to safe station-keeping for the satellites it manages, ESMO must also remain vigilant to ensure that debris left in orbit from missions long since ended do not ram into these operating satellites. At the same time, ESMO maximizes data collection to ensure the continuity and quality of NASA Earth science data. In addition to being responsible for flight operations and data acquisitions for six missions, ESMO has roles in data acquisition and/or constellation management for eight other Earth science missions, totaling involvement in 14 out of 20 missions. Part two of this article (to be featured in a subsequent issue) will focus on ESMO's Earth Observing System Data and Operations System (EDOS).

continued on page 2



The U.S./European Jason-3 satellite has produced its first map of sea surface height, which corresponds well to data from its predecessor, Jason-2. Red shades indicate areas with higher-than-normal sea levels; blue shades indicate areas with lower-than-normal sea level. El Niño is visible as the red blob in the eastern equatorial Pacific.

Extending the timeline of ocean surface topography measurements begun by the Topex/Poseidon and Jason-1 and -2 satellites, Jason 3 will make highly detailed measurements of sea-level on Earth to gain insight into ocean circulation and climate change.

Image credit: NASA/JPL Ocean Surface Topography Team

In This Issue

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

We reported in our last issue the successful launch of Jason-3 on January 17, 2016. All systems are on and working well as of this writing. The satellite has maneuvered into orbit about 80 seconds behind Jason-2 and is collecting data at essentially the same time and place as Jason-2. It will stay in this tandem orbit for about six months while scientists and engineers take a careful look at any differences between Jason-2 and Jason-3. After that, Jason-2 will move to an interleaved orbit (ground tracks halfway between those of Jason-3) where the two missions collectively will provide double the observational coverage of the global ocean. The image on the front cover shows the "first light" image from Jason-3 and a corresponding image from Jason-2. For more information, please see *www.jpl.nasa.gov/news/news.php?feature=6112.*

Jason-3 is a partnership that includes NOAA, NASA, CNES, and EUMETSAT. Its nominal three-year mission will continue nearly a quarter-century record of ocean surface topography measurements. Scientists use these data to calculate the speed and direction of ocean surface currents and to gauge the distribution of solar energy stored in the ocean. This information is applied to a variety of applications including monitoring climate change, tracking phenomena such as El Niño, improving the accuracy of hurricane intensity forecasts, as well as other commercial and operational applications. To read about the most recent Ocean Surface Topography Science Team meeting see the article on page 14 of this issue.

Our Earth science fleet continues to achieve milestones in terms of longevity. March 17, 2016 marked the fourteenth anniversary of the launch of the GRACE mission. The mission has long outlived its original five-year mission and the extended mission continues to produce new science. To date, the mission has produced 152 *Release-05* monthly measurements of Earth's gravity field (out of a maximum possible 168[1]) that are improved by approximately a factor of two over the previous *Release-04* product. In addition, the 2015 NASA Senior Review extended the GRACE mission to 2019. Please turn to page 25 of this issue to read a summary of the most recent GRACE Science Team Meeting.

GRACE has now been in operation almost 10 years past the planned mission lifetime. The twin satellites have been experiencing degradation in the battery performance since 2011. Nevertheless, the spacecrafts

[1] To save energy the instruments onboard the GRACE satellites are turned off in a regular cycle. This leads to data gaps, and hence there are only usable data for 152 out of the 168 months that GRACE has been in orbit.

continue to function and collect nominal science data at this time. The GRACE team is carefully managing the satellite propellant and the remaining battery life for both satellites, developing and testing procedures for adjusting loads and for adjusting attitude to minimize solar power production to help facilitate lower battery temperature, should this capability be necessary. Best estimates at present suggest that the effects of atmospheric drag will end the mission sometime between mid-2017 and the first quarter of 2018. It is expected that nominal science data will be collected during the remainder of the mission life.

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. The multinational mission operations team at German Space Operations Centre (GSOC), GFZ, JPL, and UT/CSR, together with industry support, continues to work towards minimizing any data gap that might occur before GRACE-FO continues these measurements into the next decade.

In addition, April 28, 2016 marks the tenth anniversary of the launch of CloudSat and CALIPSO. The two missions were comanifest on the same launch vehicle and have worked together to significantly enhance our understanding of the three-dimensional structure of clouds and aerosols in Earth's atmosphere with broad applications for science and society. Data from the three CALIPSO instruments—Cloud–Aerosol Lidar with Orthogonal Polarization (CALIOP), Imaging Infrared Radiometer (IIR), and Wide–Field Camera (WFC)—and from the CloudSat Cloud-Profiling Radar (CPR) have been collected almost continuously and all instruments have performed exceptionally.

CloudSat uniquely observes the vertical structure of cloud microphysical properties and light precipitation, while CALIPSO has greatly increased our ability to understand the vertical structure of aerosols and thin cirrus clouds as well as several important aerosol and cloud radiative properties. CALIPSO and CloudSat were the impetus for the development of the A-Train. Both operate in close proximity to each other to allow for collocated measurements. The A-Train missions demonstrated enhanced science capabilities through constellation flying, in particular the advancement of geophysical retrieval algorithms and science through the synergistic use of intersatellite instruments, which has enabled a leap forward in NASA's Earth observing capabilities.

The Earth Observer plans a detailed article on the tenth anniversary of CloudSat and CALIPSO in an upcoming issue but for now congratulations are in order for both teams on reaching this impressive milestone!

Looking ahead to the future, NASA has announced two winners from among 14 proposals submitted in response to the third Earth Venture Instrument (EVI-3) announcement of opportunity.

The Multi-Angle Imager for Aerosols (MAIA) will make multiangle radiometric and polarimetric measurements, both of which are needed to characterize the sizes, compositions, and properties of particulate matter in air pollution. As part of the investigation, researchers will combine MAIA measurements with population health records to better understand the connections between aerosol pollutants and health effects. **David Diner** [JPL] is the principal investigator; he leads a team with extensive experience in polarimetry, air pollution, and human health. The team includes partnerships with LaRC and GSFC, as well as several universities, federal research organizations, and international partners.

The Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS) investigation will consist of 12 CubeSats, each about one foot long and weighing 8.5 lbs (~3.9 kg), that use scanning microwave radiometers to measure temperature, humidity, precipitation, and cloud properties. The CubeSats will be launched into three separate orbital planes to enable the overall constellation to monitor changes in tropical cyclones as frequently as every 21 minutes. **William Blackwell** [MIT's Lincoln Laboratory] is the principal investigator. The TROPICS team has previous experience developing CubeSats and analyzing satellite measurements of storms, and includes partnerships with WFC and GSFC, several universities, and NOAA.

NASA's Earth Venture Program[2] was created in response to a recommendation in the 2007 Earth Science Decadal Survey calling for periodic windows of opportunity to provide innovative measurements to address Earth science research and accommodate new scientific priorities. In addition to EVI investigations, which are for instrument development, the program also provides opportunities to propose, develop, and implement suborbital investigations (EVS) and full missions (EVM). More details on the program and the previous missions chosen can be found at *science.nasa.gov/about-us/smd-programs/earth-system-science-pathfinder.*

Congratulations to the MAIA and TROPICS teams! ■

[2] The Venture Program was described in "A New Venture for NASA Earth Science" in the September–October 2010 issue of *The Earth Observer* [**Volume 22**, **Issue 5**, pp. 13-18].

Note: List of undefined acronyms from the *Editor's Corner* and the *Table of Contents* can be found on **page 37**.

Earth Science Mission Operations, Part I: Flight Operations—Orchestrating NASA's Fleet of Earth Observing Satellites

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Introduction

Since the 1957 launch of *Sputnik* thrust mankind into the space age, the U.S. and other space-faring nations have placed thousands of artificial satellites into a variety of Earth-centered orbits where they historically or currently conduct a broad array of missions. After over a half-century of exploration, the "space" immediately adjacent to Earth is quite crowded—not only with operating satellites, but also with various kinds of debris from those that have long since ceased to function.

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Whatever a satellite's objectives, its orbit and orientation can be precisely determined using fundamental principles of physics including Johannes Kepler's three laws of satellite motion and Isaac Newton's laws of gravitation. Kepler and his contemporaries were able to use these equations to work out precise positions of orbiting bodies. With the dawn of the space age, the number of objects in orbit significantly increased and calculations became more challenging, but the corresponding rise of computer technologies kept things manageable. What becomes more complicated is maintaining the orbits of all these satellites. With agencies across international borders launching satellites with many disparate missions and requirements, the situation quickly becomes quite complex and challenging to manage. In the case of NASA, its current Earth-observing fleet consists of 20 missions, as shown in **Figure 1,** each conducting an independent mission and some flying in close proximity to one another in precisely engineered formations (as elaborated on later). With all this "stuff" flying around, there is a clear need for careful planning to keep them all flying safely.

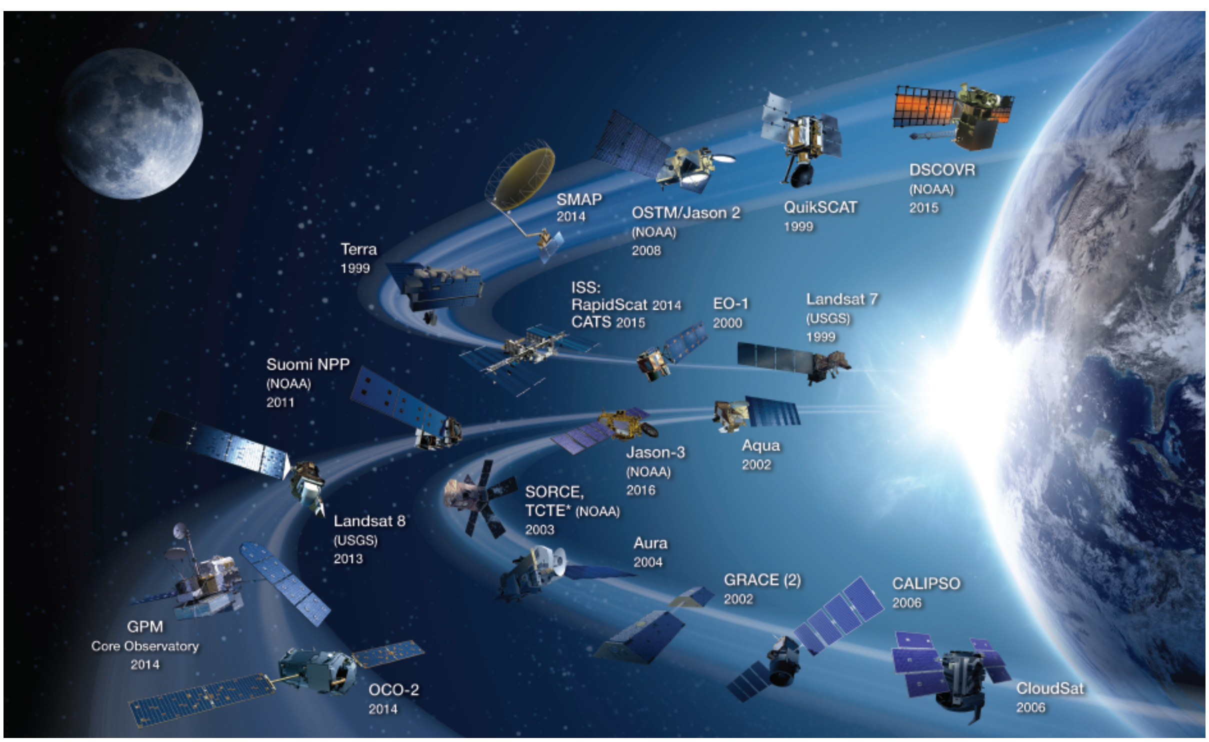

Figure 1. NASA's current Earth-observing fleet includes 20 missions. Out of the 20 missions, 2 are payloads onboard the International Space Station (ISS)—the Rapid Scatterometer (RapidScat) and Clouds Aerosol Transport System (CATS) missions. This leaves 18 free-flying missions. Note: This diagram does not represent the actual orbital tracks of each mission or the actual groupings of satellites. * TCTE is a separate NOAA payload onboard the U.S. Air Force's Space Test Program Satellite (STPSat)-3 **Image credit:** NASA

Earth Science Mission Operations

NASA's Earth Science Mission Operations Project (hereinafter, the *Project* or *ESMO)*, at NASA's Goddard Space Flight Center (GSFC) is responsible for the safe operation of six of NASA's Earth-science satellites. In the words of **Eric Moyer** [GSFC—*ESMO's Deputy Project Manager-Technical*], the overall goal of ESMO is, "…to safely operate and manage the missions while maximizing data collection to ensure the continuity and quality of NASA Earth-science data." Toward that end, as shown in **Figure 2**, ESMO has varying levels of involvement in 14 of the 20 Earth science missions shown in Figure 1. The three roles listed in the figure's legend will be explained in more detail in the sections that follow.

ESMO has two operational components. The first is the Flight Operations Segment (FOS) that is responsible for maintaining the satellite's prescribed orbit and commanding and controlling the spacecraft and its instruments. Each of these responsibilities will be described in this article. The second operational component is the Earth Observing System (EOS) Data and Operations System (EDOS), a complex network of computers and communications systems that is responsible for acquiring, processing, and delivering science data for all supported missions, as well as satellite and instrument systems data for the Terra, Aqua, and Aura platforms—sometimes referred to as the Earth Observing System's (EOS) "Flagship" missions. The specific components of EDOS will not be discussed further herein, except as they interface with FOS for coordinating mission operations, but these will be expanded on in a future article[1].

ESMO is responsible for flight operations for six missions: Terra, Aqua, Aura, the Global Precipitation Measurement (GPM) Core Observatory, Earth Observing (EO)-1, and the Solar Radiation and Climate Experiment (SORCE).

ESMO Flight Operations Segment

ESMO is responsible for flight operations for six missions: Terra, Aqua, Aura, the Global Precipitation Measurement (GPM) Core Observatory, Earth Observing (EO)-1, and the Solar Radiation and Climate Experiment (SORCE)—marked with triangles in Figure 2. ESMO assumes responsibility for operation of a given mission following successful launch and early-orbit activities; its involvement then continues through to the end of the mission including the eventual deactivation phases after a satellite's productivity is

[1] To learn more about EDOS, visit *earthdata.nasa.gov/about/science-system-description/esmo-components*.

Figure 2. NASA currently has 18 free-flying Earth-observing satellites in orbit as of this writing. The 14 depicted here, have links with ESMO by one or more connections that are shown in the legend. NOTE: This diagram does not represent the actual orbital tracks of each mission or the actual groupings of satellites. **Image credit:** NASA

ESMO ensures the health and safety of all the missions it manages by satisfying all the requirements for each mission, which includes providing the scientific community with high-quality data products in a timely manner.

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For Terra, Aqua, and Aura, the EOS Operations Center (EOC) located at GSFC constitutes the FOS. It provides mission planning and scheduling as well as command and telemetry systems to operate the spacecraft and monitor health and safety of the spacecraft and instruments. EOC provides software tools to each instrument team so they can schedule activities while ensuring conflict-free schedules. Once the teams develop their schedules for operations (e.g., planning procedures for special observation modes, calibration, and data readouts), the FOS executes them while assuring mission safety. The EOC is always alert to accommodate unplanned schedule changes[2] by developing and implementing contingency plans. The FOS accomplishes much of its work by coordinating with the Instrument Operation Teams and Science Mission Operation Working Group (MOWG) made up of the project scientists for each mission and (in the case of the Flagship missions) representatives from the science teams of each individual instrument—including international partners.

FOS Orbit Maintenance Services

Even absent the threats posed by other spacecraft and rogue space debris described in the Introduction, space would be a dangerous environment simply by virtue of the harsh conditions that satellites endure while in orbit. They are subject to extreme variations in temperature and pressure as well as the notoriously difficult task of predicting the impacts of *space weather*[3]. All of these can place additional *drag* (or atmospheric friction) on the spacecraft and alter its orbit. These impacts must be compensated for to allow the satellites to continue to operate safely and maintain continuous Earth monitoring.

The remainder of this section discusses FOS's Orbit Maintenance services. First, the basic orbital maneuvers are described, followed by two specific areas where such orbital maneuvers are used: constellation flying, and tracking debris and preventing collisions.

Orbital Maneuvers

Whether the orbital maneuver, or *burn*, is to overcome the effects of drag, or to keep a satellite from drifting too close to another, or an emergency maneuver to avoid a potential collision with another object in space, any effort to maintain or move a satellite's position in orbit requires maneuvers using the satellite's propulsion subsystem to fire thrusters to bring about a change in the satellite's orbit. A maneuver may involve one or more burns. ESMO performs the following three types of orbital maneuvers:

- ***Orbit Raising***. This type of maneuver increases the spacecraft's *semi-major axis*[4]. This category encompasses so-called *drag makeup maneuvers*, which counteract the effects of atmospheric drag and resets the satellite's orbit. Orbit-raising maneuvers are also used for risk mitigation to avoid orbital debris (see below) and to position new satellites into the mission's specified orbital location.

- ***Orbit Lowering***. This type of maneuver decreases the spacecraft's semi-major axis. Examples include *braking maneuvers* used to avoid exiting a constellation control box (discussed later), *risk-mitigation maneuvers* to avoid orbital debris, and *exit maneuvers* for satellites leaving their nominal orbital locations.

- ***Inclination Adjust***. This type of maneuver maintains the orbit's *Mean Local Time* (time of crossing overhead) in a pre-specified range based on mission science objectives. These are performed typically once or twice per year.

[2] Unscheduled changes might include special observations by any one of the instrument teams and maneuvers to avoid collisions with debris or satellites not under NASA control.
[3] Space weather includes natural processes in space that can affect the near-Earth environment, satellites, and human space travel, e.g., magnetospheric disturbances, solar coronal events, and solar wind.
[4] This term comes from basic orbital mechanics. An orbiting satellite follows a path in the shape of an ellipse. The *semi-major axis* is one-half of the major axis of the ellipse and represents a satellite's mean distance from the *primary*—or the body being orbited, in this case, Earth. For a primer on orbital mechanics, including definitions of important terms, the laws of orbital motion and universal gravitation referred to in the Introduction, refer to *www.braeunig.us/space/orbmech.htm.*

Once a need for a satellite maneuver is established and its desired new position or orbit is determined, the following process is implemented:

1. The Flight Dynamics Team (FDT) determines the change in velocity needed to achieve the required height and a *yaw angle*[5] to reach the desired inclination.
2. The FDT provides recommended maneuver parameters to the Flight Operations Team (FOT).
3. A command authorization meeting is conducted to verify readiness to perform the maneuver.
4. Once approved, the FOT configures the spacecraft and uploads the desired parameters to have the control system perform the maneuver.
5. The satellite control system responds using onboard software to fire the thrusters to achieve the desired maneuver, thereby relocating the satellite.

Constellation Flying: The A-Train and Morning Constellation

In order to study Earth as a system of systems, comprehensive global observations are required. Hence, coordinated measurements of Earth's environment have long been a NASA priority. Early proposals for Earth-observing systems envisioned a vast number of instruments on a single large platform. For a variety of reasons, this proved difficult to implement and this approach was eventually abandoned in favor of a number of medium-sized and smaller platforms[6]. This change in direction of flight hardware development led to a corresponding technological development of so-called *constellation flying* concepts, whereby several missions would fly in a carefully engineered orbital formation. Constellation flying allows all instruments in the formation to observe the same location (or phenomenon) within a near-synchronous, short time interval. In essence, the effect is similar—though not identical—to what would be achieved if all of the instruments in the formation were flying on the same platform.

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Constellation flying allows for *synergistic observations*—meaning that the combined observing capability of the whole formation is greater than the sum of each mission operating independently. For example, among each constellation there are instruments with differing observing capabilities that measure similar environmental parameters (e.g., aerosols, clouds, land cover, ice extent, air quality, and water pollution). These combined observations allow the opportunity to further study the targeted parameter properties to learn how and why they change. Combinations of coincident measurements of different properties also provides the opportunity to understand interrelated processes and their interactions—e.g., hurricane development from sea surface temperature and clouds, or the impact of drought on vegetation productivity.

NASA has developed two satellite constellations: the Afternoon, or "A-Train," Constellation and Morning Constellation. The current configurations of both the Morning and Afternoon Constellations are shown in **Figure 3**; the **Table**[7] on page 8 summarizes the past and present members of each constellation. ESMO provides crucial support for both of these constellations. See the sidebar page 9 to learn *More on the Morning Constellation*.

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[5] In flight dynamics, yaw is one of three angles of rotation around the spacecraft's center of mass (the other two being pitch and roll). In a three-dimensional Cartesian frame of reference (i.e., x, y, z) yaw represents rotation around the z-axis.

[6] See "The Enduring Legacy of the Earth Observing System, Part II: Creating a Global Observing System—Challenges and Opportunities" in the May–June 2011 issue of *The Earth Observer* [**Volume 23, Issue 3**, pp. 4-14].

[7] This Table is modified from a version that appears in "Collision avoidance: Coordination of predicted conjunctions between NASA satellites and satellites of other countries" by Angelita Kelly and Wynn Watson that can be viewed at *www.amostech.com/TechnicalPapers/2014/Poster/KELLY.pdf.* The Kelly and Watson article covers many of the same topics covered in this article.

Table. Past and present members of NASA's Earth-observing satellite constellations.

Satellite	Mission Summary	Duration	Responsible Organization
Afternoon Constellation (A-Train)			
Aqua	Aqua (Latin for *water*) is named for the mission's focus on Earth's water cycle, including evaporation from the ocean, water vapor in the atmosphere, clouds, precipitation, soil moisture, sea ice, land ice, and snow cover on the land and ice. Many additional variables are also measured.	May 4, 2002 – present	NASA
Aura	Aura (Latin for *air*) studies Earth's atmospheric ozone, air quality, and climate. The mission is designed to conduct research on the composition, chemistry, and dynamics of Earth's atmosphere.	July 15, 2004 – present	NASA
PARASOL	PARASOL collected polarized light measurements that allow better characterization of clouds and aerosols in Earth's atmosphere. **NOTE**: PARASOL exited the constellation in December 2009, and was decommissioned in late 2013.	December 18, 2004 – December 2013	CNES
CALIPSO	CALIPSO has a spaceborne lidar onboard, which when combined with data from two passive instruments onboard or with those from instruments on other platforms leads to improved understanding of the role aerosols and cirrus clouds play in regulating Earth's climate.	April 28, 2006 – present	NASA
CloudSat	CloudSat carries a powerful Cloud Profiling Radar that provides a detailed view of clouds, which allow scientists to better characterize the role clouds play in regulating Earth's climate.	April 28, 2006 – present	NASA
GCOM-W1	GCOM-W1 observes integrated water vapor, integrated cloud liquid water, precipitation, sea surface wind speed, sea surface temperature, sea ice concentration, snow water equivalent, and soil moisture.	May 18, 2012 – present	JAXA
OCO-2	OCO-2 is equipped with three grating spectrometers that make global, space-based observations of the column-integrated concentration of carbon dioxide, a critical greenhouse gas.	July 2, 2014 – present	JPL
Morning Constellation			
Landsat 5	Landsat 5 collected specialized digital photographs of Earth's continents and surrounding coastal regions, enabling the study of many aspects of our planet and the evaluation of the dynamic changes caused by both natural processes and human practices.	March 1, 1984 – June 5, 2013	USGS
Landsat 7	Landsat 7 provides global coverage, and spectral characteristics that allow comparisons for global and regional change detection. The mission provides image data to various international users throughout the world particularly during times of sudden global changes (e.g., earthquakes or floods).	April 15, 1999 – present	USGS
Terra	Terra (Latin for *land*) is a multinational, multidisciplinary mission that helps us to understand how the complex coupled Earth's systems of air, land, water, and life are linked.	December 18, 1999 – present	NASA
EO-1	EO-1 was originally a technology testbed designed to help develop and validate a number of instrument and spacecraft bus breakthrough technologies designed for use on future Earth-imaging observatories; it has operated 14 years beyond its orginal one-year mission.	November 21, 2000 – present	NASA
SAC–C	SAC-C provided multispectral imaging of terrestrial and coastal environments; studied the structure and dynamics of Earth's atmosphere, ionosphere and geomagnetic field; and measured space radiation in the environment.	November 21, 2000 – August 15, 2013	CONAE
Landsat 8	Landsat 8 continues the Landsat program's critical role in monitoring, understanding and managing the resources needed for human sustainment such as food, water and forests; provides continuity with the 40+ year Landsat land imaging dataset.	February 11, 2013 – present	USGS

List of acronyms used in Table—CNES: Center Nationale d'Études Spatiale [French Space Agency]; CALIPSO: Cloud–Aerosol Lidar with Infrared Pathfinder Satellite Observations; CONAE: Comisión Nacional de Actividades Espaciales [Argentinian Space Agency]; EO-1: Earth Observing-1; GCOM-W1: Global Change Observation Mission–Water 1; JAXA: Japan Aerospace Exploration Agency; OCO-2: Orbiting Carbon Observatory–2; PARASOL: Polarization and Anisotropy of Reflectances for Atmospheric Science coupled with Observations from a Lidar; SAC-C: Satélite de Aplicaciones Científicas-C; USGS: United States Geological Survey.

While other satellites fly in constellations (e.g., the U.S. Global Positioning Satellites), what sets these two NASA constellations apart is the fact that they are *heterogeneous constellations* (i.e., they involve diverse groups of spacecraft and instrument sensors) that are international in scope, involving space agencies from the U.S., Argentina, Brazil, Canada, France, Finland, Japan, the Netherlands, and the U.K. Each mission is independently managed by its respective nation's responsible organizations. ESMO plays a key role in coordinating the interactions between the international partners and maintaining safe operation of the overall formation.

With regard to how the FOS interacts with the actual platforms, each satellite in the Morning and Afternoon Constellations operates within a *control box*—a prescribed area within which the mission can safely operate[8]. The satellites are allowed to fly freely in their boxes until they reach their respective box boundaries, at which time their orbits are adjusted through maneuvers that are commanded from the ground, as described previously. These satellite maneuvers not only keep the satellites from colliding with one another, but also maintain their precise *pointing* (or observing geometries), as this is an absolute requirement for consistent science observations.

[8] To learn more about how control boxes work (for example) in the specific case of the A-Train, visit *atrain.nasa.gov/control_boxes.php*.

While other satellites fly in constellations, what sets these two NASA Constellations apart is the fact that they are heterogeneous constellations that are international in scope, involving space agencies from the U.S., Argentina, Brazil, Canada, France, Finland, Japan, the Netherlands, and the U.K.

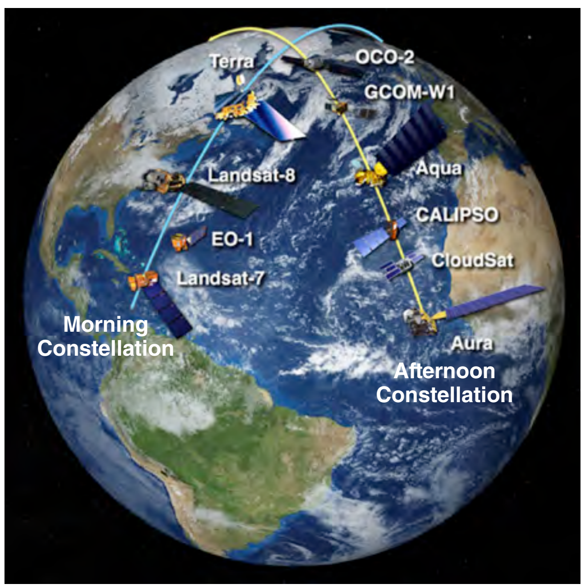

Figure 3. This figure illustrates orbit directions for the Morning and A-Train constellations. Acronyms used here are defined below the Table on page 8. **Image credit**: NASA.

More on the Morning Constellation

The Morning Constellation's primary focus is on land science. It has included contributions from the U.S., Canada, Argentina, Denmark, Italy, France, and Japan (see Table). The Satélite de Aplicaciones Científicas-C (SAC-C), provided by Argentina, was declared lost in August 2013. The formation currently consists of three satellites: Terra, Landsat-7, and Landsat-8, with equator crossing times between 10:00 and 10:30 AM.

Earth Observing (EO)-1 was also part of the Morning Constellation when it was initiated. However, it exited in 2013 when its fuel supply began to run low. The Morning Constellation Exit Plan, which all participants agreed to prior to becoming part of the formation, stipulates that: in order to preserve the constellation's orbit, all missions must depart the constellation while they still have sufficient fuel to safely exit. EO-1 has continued collecting science data since exiting the constellation and is tentatively scheduled for decommissioning by March 2017[1].

[1] To learn more about EO-1, please see "EO-1: 15 Years After the Start of Its 'One-Year Mission'" in the January–February 2016 issue of *The Earth Observer* [**Volume 28, Issue 1**, pp. 4-14].

In the specific case of the A-Train, the Constellation MOWG assesses the potential impact of any proposed changes in operations of the Constellation. The MOWG has agreed to a set of guidelines, processes, and procedures for flying together and established a process to ensure orbital safety using tools provided by ESMO, while allowing the teams to maintain autonomy over their missions. Safety of the entire constellation is the overriding concern and forms the basis for all the guidelines. These agreements include the baseline orbital configuration, a forum for defining changes to the constellation configuration, data exchange, coordination of field campaigns, and a forum for discussing and resolving issues among the satellite member teams.

Even the smallest debris fragments have the potential to disrupt space operations and severely damage satellites—typically worth tens or even hundreds of millions of dollars.

Tracking Debris and Preventing Collisions

ESMO must not only keep all the current satellites in orbit from colliding with each other, they must remain vigilant to make sure that space junk does not ram into their satellites. Even the smallest debris fragments have the potential to disrupt space operations and severely damage satellites—typically worth tens or even hundreds of millions of dollars.

The NASA Orbital Debris Program Office (ODPO) at Johnson Space Center[9] is the international lead for taking measurements, developing models of the existing and future debris fields, and participating in the development of mitigating procedures to protect users of the space environment. According to documentation from the ODPO[10], between the surface and geostationary Earth orbit [35,786 km (22,236 mi)], there are estimated to be 500,000 hazardous pieces of debris larger than 1 cm (~0.4 in) in orbit. About 20,000 of these pieces of debris greater than 5 cm (~2 in) are being actively tracked. **Figure 4** is a representation of the actively tracked debris in low-Earth orbit [altitude <2000 km (~1243 mi)].

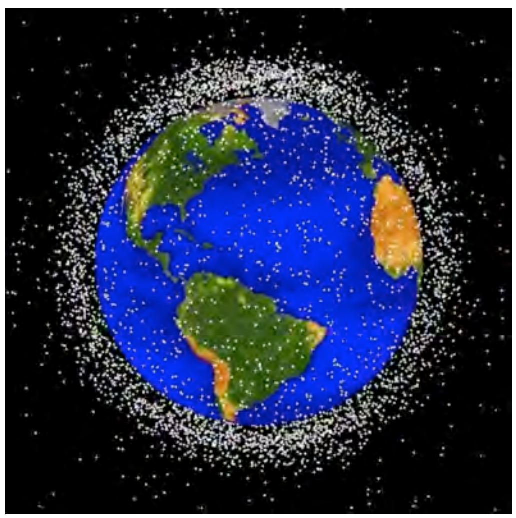

Figure 4. A computer simulation of objects in low-Earth orbit [altitude less than 2000 km (~1243 mi)] that are currently being tracked. Approximately 95% of the objects in this illustration are orbital debris. The tracked objects are represented by dots, although the dot sizes and locations are not to scale with respect to the Earth. **Image credit**: NASA

The NASA capability for tracking satellites and predicting position in their orbits is provided by the Conjunction Assessment Risk Analysis (CARA) team[11]. CARA makes use of the debris field models to assess risks of debris collisions with NASA satellites. CARA presently provides support for approximately 70 satellites, so far requiring processing over 1,000,000 close-approach messages, and has assisted with about 100 avoidance maneuvers.

NASA defines a *conjunction* as a close approach between two orbiting objects. *Conjunction analysis*, then, predicts the location and time when the two objects are at their closest distance. CARA works closely with the Department of Defense's Joint Space Operations Center (JSpOC), which has responsibility for maintaining a catalog of all objects orbiting Earth. CARA employs algorithms that analyze close approaches between satellites and quantify the risk of a collision. The results of this analysis is in turn used to inform the FOS what mitigation is needed—i.e., one of the maneuvers described above or some other action. The CARA team provides a

[9] For more on the ODPO, access *www.orbitaldebris.jsc.nasa.gov.*

[10] For details refer to *orbitaldebris.jsc.nasa.gov/faqs.html#3* and *orbitaldebris.jsc.nasa.gov/measure/radar.html.*

[11] To learn more about CARA activities, visit *satellitesafety.gsfc.nasa.gov.*

recommendation, which the FOS can choose to implement if they agree the maneuver is necessary and safe. If the maneuver will require a spacecraft to move outside of its control box, the FOS will advise the MOWG.

Ensuring safety of NASA's missions is a continuing activity for the FOS. Once CARA predicts a conjunction, maneuver planning begins approximately three days in advance of the potential event. Finalizing a maneuver is an iterative process involving JSpOC, CARA, and the FOS, since a maneuver may lead to a conjunction with another object. While the maneuver is being planned, maintaining or returning the spacecraft to its prescribed orbit needs to be considered. Other factors—such as debris and changes in drag—have to be taken into account. To learn about some specific examples where CARA has had to take action please see *ESMO Protects the Safety of NASA's Earth-Observing Satellites,* below.

Ensuring safety of NASA's missions is a continuing activity for the FOS.

ESMO Protects the Safety of NASA's Earth-Observing Satellites

On September 3, 2013, NASA's Conjunction Assessment Risk Analysis (CARA) team predicted a close approach between the Aura satellite and the Chinese Shijian (SJ)-11-02 satellite, known only as an "experimental satellite." The concern was that the Chinese satellite would enter an orbit very similar to that of the Morning and A-Train Constellations. Based on the CARA predictions, the FOS flight controllers coordinated with the Aura Science Team and prepared a risk mitigation maneuver to avoid the close approach and a possible collision. However, because FOS was unable to communicate directly with the Chinese, they did not know whether Shijian was capable of maneuvering and might do so—possibly making the situation worse. NASA sent a request through the U.S. Department of State to its counterpart in China to let their space agency know of NASA's planned maneuver, but there was no direct two-way coordination. In the end, both satellites maneuvered, and passed each other safely. From this episode, it became clear that the coordination between nations was needed for future close approaches. In November 2015 the U.S. and China agreed to establish a direct link—or "hotline"—allowing both nations to easily share information about their space activities. This *space hotline* will help both countries' civilian and military space agencies discuss "potential collisions, approaches, or tests." NASA still cannot communicate directly with its Chinese counterpart, however, nor can the Department of Defense's Joint Space Operations Center (JSpOC) represent NASA's interests because of the U.S. Congressional ban that prevents NASA from engaging in bilateral agreements and coordination with China. As of this writing, NASA will continue to deal with China on potential satellite collisions through the U.S. Department of State.

The FOS team had to disrupt the A-Train on several occasions prior to this event. For example, Cloudsat was moved out of the constellation in September 2012 to diagnose a power problem before it was allowed to re-enter the constellation in formation with CALIPSO. If CloudSat were to have experienced a spacecraft power failure while in the constellation, there would be no ability to control its movement and it would have forced a disruption of the entire A-Train, possibly compromising scheduled science observations. On another occasion in 2012 there was a potential collision between NASA's Fermi Gamma-ray Space Telescope (which is managed by NASA's Space Science Mission Operations Project) and a defunct Soviet COSMOS spy-satellite. A simple thruster burn took the NASA satellite well out of danger. After each event, the satellites were returned to their respective nominal orbits.

Another noteworthy and now regular interaction between mission teams is between the the Global Precipitation Measurement (GPM) Core Observatory and the International Space Station (ISS) groups. The GPM satellite and ISS occupy similar orbits: 65° inclination and 400 km (~ 249 mi) altitude and 59° inclination and ~400 km altitude, respectively. The FOS, on behalf of GPM, communicates regularly with the ISS Trajectory Operations Officer (TOPO) to make sure that performed maneuvers are safe and to evaluate jettisoned objects, such as Cubesats, from the ISS and to allow sufficient time for the object to be cataloged by JSpOC and GPM to perform a risk-mitigation maneuver if warranted.

These and additional instances are documented on the ESMO website at *satellitesafety.gsfc.nasa.gov/case_histories.html.*

Networks: Collecting Data in Space and on the Ground

Crucial links connecting the ESMO Project with the orbiting satellites it oversees are NASA's Near Earth Network (NEN) and Space Network (SN), both managed at GSFC[12]. These networks are comprised of tracking stations distributed throughout the world that provide telemetry, tracking, and commanding services for about 40 customers' missions—including NASA's Earth Science, Space Science, and Human Explorations missions, other U.S. government agencies' missions, and international and commercial missions in low-Earth and geostationary orbits. The NEN consists of the Ground Network (GN) and the Satellite Laser Ranging Network and coordinates with the Tracking and Data Recording Satellite (TDRS) that is part of SN. Many of the NEN GN sites are located in polar locations that provide service to high-inclination polar-orbiting spacecraft, such as those in the A-Train and the Morning Constellations. There are 16 of these stations throughout the world; NASA owns 6 of them[13].

These networks are comprised of tracking stations distributed throughout the world that provide telemetry, tracking, and commanding services for about 40 customers' missions—including NASA's Earth Science, Space Science, and Human Explorations missions, other U.S. government agencies' missions, and international and commercial missions in low-Earth and geostationary orbits.

ESMO Brings the Data Together for Mission Maintenance

Figure 5 depicts how all these interfaces come together to coordinate operations of the Terra mission. Since it has one of the most extensive "webs" of interfaces, the specific case of Terra can serve as an illustration of how the process works. All missions that ESMO oversees have at least one, and in many cases several, of the components depicted in Figure 5.

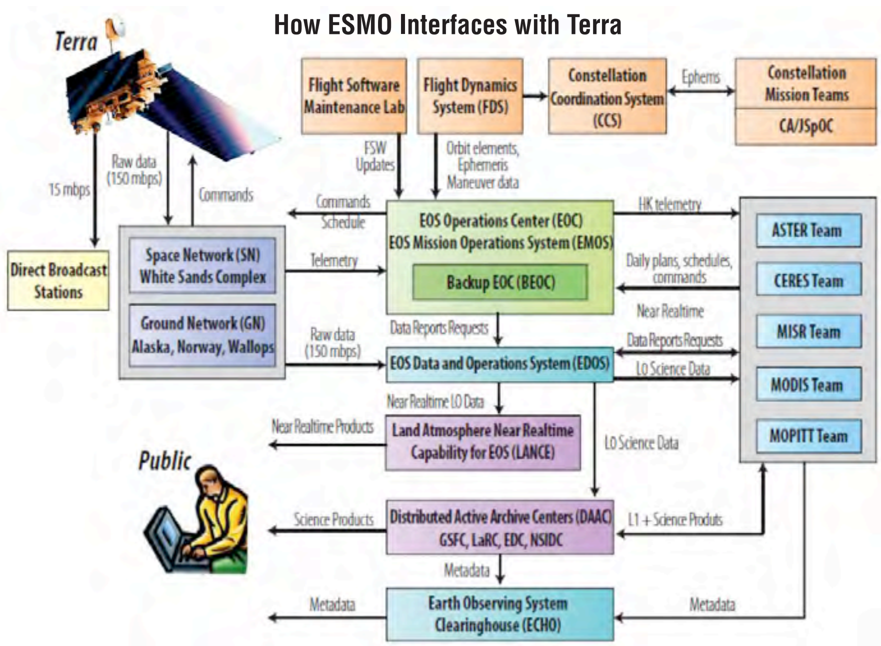

Figure 5. This block diagram shows many interfaces between ESMO and NASA's Terra mission. The right side of the diagram indicates each of Terra's instrument teams. The top shows the Flight Operations interfaces while the center and left blocks represent data acquisition, processing and distribution. All other missions for which ESMO coordinates operations use at least one, if not several, of the interfaces depicted here. **Image credit:** NASA

This article focuses primarily on FOS, but there is a point where the story of ESMO cannot be completely told without mentioning its second crucial component. As its name implies, EDOS, or the EOS Data and Operations System, is responsible for processing the vast amount of science and engineering data received from the spacecraft and instruments through SN and NEN and processing the raw instrument data into *Level 0* data, which are time-stamped and geolocated over a specified time interval. These data are then sent to the appropriate Distributed Active Archive Centers (DAACs) and Science Investigators Processing System (SIPS) for further processing

[12] Visit *www.nasa.gov/directorates/heo/scan/services/networks/index.html* to learn more about NASA's Network Services, which include Near Earth, Space, and Deep Space Networks (the latter discussed in this article).

[13] All the NEN GN sites are listed at *www.nasa.gov/directorates/heo/scan/services/networks/txt_nen.html.*

and storage. The process employs several back-up capabilities to insure that no data are lost. EDOS also maintains the ground equipment, identifies hardware trends for upgrades, and plans for future missions.

EDOS works with EOS Real-time Processing System (ERPS) to provide a communication interface between the control center and ground stations for Terra, as well as for Aqua and Aura. EDOS also provides a route for near-real-time data for the EOS Flagship missions using the Rapid Response System and the Land, Atmosphere Near-Real-Time Capability for EOS (LANCE). These services provide data users with much quicker access to satellite data—usually within three hours of acquisition.

Meanwhile, the FOS at GSFC is responsible for the execution of in-orbit activities involving the satellite and their instruments and subsystems. The flight operations team (FOT) is accessible and ready for any emergency 24/7 to coordinate with all partners to execute commands to ensure safety of each mission. The FOT has already performed thousands of in-orbit activities over Terra's approximately 16-year lifetime, and conducts approximately 11,000 contacts each year through the NEN and TDRS. The FOT manages the satellite flight recorders and has recovered 99.4% of the science data taken in orbit. Further, the FOT conducts special spacecraft engineering and instrument calibration activities that have included 88 drag make-up maneuvers, 42 inclination adjust maneuvers, 160 Lunar Calibration attitude maneuvers for the Moderate Resolution Imaging Spectroradiometer (MODIS), spacecraft clock maintenance, and anomaly detection and recovery activities. Over the past three years alone, the FOT has responded to 15 anomalies regarding the Terra spacecraft, instruments, and ground system.

As emphasized in this article, mission safety is the highest priority for the ESMO's FOS.

Future Plans for FOS

ESMO continues to improve its capabilities with innovative software and employing the latest hardware development. In order to facilitate communications amongst NASA's Morning and A-Train Constellations, ESMO established a Constellation Coordination System (CCS) involving all the mission members. The CCS design is a web-based portal for the collaboration, data sharing, and operational planning for these missions. CCS provides "situational awareness," i.e., a means to track the operational health of the constellations as well as to share mission products and perform specific orbital analyses, all online. FOS and CARA continue to improve the system. Upgrades include streamlining the process through automation to shorten the timeline and working with NASA's Space Weather Research Center to understand operational needs for improving space weather models and obtaining better predictions of drag. Maintaining and improving security is a high priority. No intrusions to computers or relevant networks have occurred since software upgrades began in 2006.

Conclusion

As emphasized in this article, mission safety is the highest priority for the ESMO's FOS. This priority includes protecting satellites from the natural and man-made hazards of the near-Earth space environment, managing the orbits of the agency's satellites, and maintaining their position within their respective constellations. In-orbit safety includes coordination with several NASA and non-NASA national and international space agency elements and even the commercial sector. ESMO continues to perform its growing tasks as new Earth-science missions come online and operations of several existing missions are extended.

Acknowledgments

The authors wish to extend special thanks to **Eric Moyer** [GFSC—*ESMO Deputy Project Manager for Technical*] who provided valuable input into this article during the developmental stages and also provided a technical editorial review of the content, and to **Claire Parkinson** [GSFC—*Aqua Project Scientist*] for providing an additional editorial review. ■

Ocean Surface Topography Science Team Meeting

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Introduction

The 2015 Ocean Surface Topography Science Team (OSTST) Meeting was held in Reston, VA, October 19-23, 2015. The meeting took place immediately following the Ninth Coastal Altimetry Workshop (CAW), which took place in the same location on October 17-18.

The primary objectives of the OSTST Meeting were to:

- provide updates on the status of Ocean Surface Topography Mission (OSTM)/Jason-2 (hereinafter, Jason-2[1]);
- conduct splinter sessions on various corrections and altimetry data products; and
- discuss the science requirements for future altimetry missions.

The meeting lasted three-and-a-half days to accommodate discussions during dedicated roundtables for each splinter session. This report, along with all of the presentations from the plenary, splinter, and poster sessions, are available on the Archiving, Validation, and Interpretation of Satellite Oceanographic (AVISO) data website at *www.aviso.altimetry.fr/en/user-corner/science-teams/ostst-swt-science-team/ostst-2015-reston.html.*

Status Report on Current Ocean Surface Topography Missions

Jason-2 was launched in June 2008 to cover the former ground track of Jason-1 and the Ocean Topography Experiment (TOPEX)/Poseidon mission. All systems on Jason-2 are in good condition and the satellite is operating nominally after seven-and-a-half years in orbit, and no major events occurred in 2015 on the platform. The cognizant agencies (see footnote 1 for list) have approved extending the mission support to at least 2017. After switching to the redundant side of the Global Positioning Satellite Payload (GPSP-B) on September 8, 2014, several software patches have been made to that instrument, improving its performance and making it comparable to the side-A instrument (GPSP-A). From a global point of view, Jason-2 continues to collect data that meet all mission and Level-1 science requirements.

Although Jason-2 continues to perform well as of this writing, at the 2014 OSTST Meeting, an Extension of Life (EOL) phase was recommended. When the risk of losing control of Jason-2 becomes significant, NASA and its partner agencies will require that the satellite be moved to a different orbit where it poses no risk of collision with other satellites. The OSTST recommended that if Jason-2 can continue collecting scientific data when such a move becomes necessary, it should be moved to a specific orbit that is suitable for improving estimates of the marine gravity field. (This is similar to the EOL mission that Jason-1 carried out.) Since the 2014 meeting, a candidate EOL orbit has been identified; during the 2015 meeting a recommendation was adopted on the timing of the move and the specific orbit that is most desirable (see Recommendations on page 17).

Jason-3 is the next ocean surface topography mission in the series, and is being prepared for a December launch[2]. After launch and initial checkout of the instruments is complete, the plan is to maneuver it into position 80 seconds behind Jason-2, where it will spend six months while the data are evaluated relative to Jason-2. After that, Jason-2 will be moved into an orbit with ground tracks halfway between the Jason-3 track—and identical to the one flown by Jason-1 during its interleaved phase. Eventually, Jason-2 will be moved to an EOL orbit, as described previously.

During the meeting several members of the OSTST expressed a desire to issue a statement highlighting the importance of satellite altimetry for monitoring and understanding climate change in advance of the twenty-first Conference of Parties (COP-21), which was the annual review meeting for the United Nations Framework on Climate Change. Although no language was formally adopted by the team during the meeting, meeting co-chairs **Pascal Bonnefond** [Laboratoire Géoazur, Observatoire de la Côte d'Azur, Centre National d'Études Spatiale] and **Josh Willis** [NASA/Jet Propulsion Laboratory (JPL)] penned an open letter to the organizers of COP-21, signed by more than 280 supporters—many on the OSTST. Bonnefond personally delivered the letter to several key participants in COP-21. The full letter can be found at *www.change.org/p/cop21-deciders-ask-the-cop21-to-recognize-sea-level-rise-as-the-top-indicator-of-climate-change*.

Highlights from the Opening Plenary

The opening plenary session featured three keynote presentations. **Benjamin Hamlington** [Old Dominion

[1] Jason-2 is a joint mission involving NASA, the U.S. National Oceanic and Atmospheric Administration (NOAA), French Centre National d'Études Spatiales (CNES), and the European Organisation for the Exploitation of Meteoroglical Satellites (EUMETSAT).

[2] **UPDATE on Jason-3**: Since the meeting being reported on here, Jason-3 was successfully launched from Vandenberg Air Force Base on January 17, 2016, aboard a Falcon 9 launch vehicle built by SpaceX. All of Jason-3's systems and instruments are operating nominally; as of this writing it is in position behind Jason-2.

University, U.S.] discussed the record of global sea level rise throughout the twentieth century. Such estimates range from 1–2 mm/yr (~0.04 to 0.08 in/yr), depending on differences in methodology, selection of tide gauges, and estimates of vertical land motion. **Ananda Pascual** [Instituto Mediterráneo de Estudios Avanzados, Spain] discussed the Alboran Sea Experiment (ALBOREX), which used a wide array of observations including remote and *in situ* observations and numerical models to study small-scale variability and the evolution and genesis of fronts in the region. **Angélique Melet** [Laboratoire d'Études en Géophysique et Océanographie Spatiales (LEGOS), France] discussed coupled climate simulations and the large spread of results for the amount of thermal expansion of the ocean that will occur in a warming climate.

In addition to the three keynote presentations, **Lee-Lueng Fu** [JPL] presented a progress report on the Surface Water and Ocean Topography (SWOT[3]) mission, which will observe ocean surface topography at unprecedented spatial resolution but with moderate temporal resolution; it is scheduled for launch in 2020. **Pierrik Vuilleumier** [European Space Agency (ESA)] provided a brief update on the Sentinel-6/Jason Continuity of Service (CS) mission, which will be the successor to Jason-3 and will be led by ESA. Two Jason-CS satellites will be commissioned, with the first to be launched in mid-2020 and the second in 2025. **Thierry Guinle** [CNES] provided an update on the SARAL/AltiKa[4] (hereafter, AltiKa) mission, which continues to provide highly accurate altimetry data. However, there are growing concerns over the platform's reaction wheels that cast doubt on how well its precision orbit can be maintained beyond its three-year planned life in February 2016. Finally, **Jérôme Benveniste** [ESA] discussed the ESA Programs, noting that the launch of Sentinel-3A is scheduled for February 16, 2016[5].

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

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

[5] **UPDATE**: Sentinel-3A successfully launched on the scheduled date.

Highlights from the Splinter Sessions

Following the opening plenary session, focused splinter sessions were held on the following topics:

- Application Development for Operations (called Near Real Time splinter in previous meetings);
- Instrument Processing: Corrections (Troposphere and Ionosphere, Wind Speed and Sea State Bias);
- Instrument Processing: Measurement and Retracking (SAR and LRM);
- Outreach, Education, and Altimetric Data Services;
- Precise Orbit Determination;
- Quantifying Errors and Uncertainties in Altimetry Data;
- Regional and Global Calibration/Validation for Assembling a Climate Data Record;
- Science Results from Satellite Altimetry: Mean Sea Level Monitoring (How to reconcile altimetry, tide gauges, land motion, and other *in situ* observations);
- Science Results from Satellite Altimetry:
  - Mesoscale and Sub-Mesoscale Ocean Processes: Current Understanding and Preparation for SWOT
  - Large-Scale and Global Change Ocean Processes: The Ocean's Role in Climate;
- The Geoid, Mean Sea Surfaces, and Mean Dynamic Topography; and
- Tides, Internal Tides, and High-Frequency Processes.

The narrative in the next two sections focuses on only two of the splinter sessions; complete coverage can be found at the AVISO website referenced in the Introduction section.

The Geoid, Mean Sea Surfaces, and Mean Dynamic Topography

Since at least 1992 with the launch of TOPEX/Poseidon, measurements of sea surface height from space have been used to study both oceanographic and geological phenomena. Locally, the gravitational pull of underwater features like seamounts and trenches, reshape the ocean waters to follow an irregular surface known as the *geoid,* which represents Earth's mean sea level. In addition, ocean currents that are large enough to persist over many days and many kilometers further tilt the ocean surface relative to the geoid. This reshaping of the ocean's surface due to currents is referred to as the *mean dynamic topography*. The separation of the geoid and mean dynamic topography signals was a key focus of this splinter session. Two presentations in this session illustrated advancements in sorting out these signals. **Ole Andersen** [Technical University of Denmark (DTU)] presented a new estimate of the mean sea surface in the Arctic based on data from many altimeters, including data from the altimeter onboard the European Space Agency's Cryosat-II spacecraft (launched in 2010). Although the mean sea surface was well measured over much of the world, the addition of CryoSat-II data has greatly improved estimates in the Arctic. By removing an estimate of the geoid, the mean dynamic topography is revealed (see **Figure 1**), showing the intricate currents that persist in the Arctic Ocean.

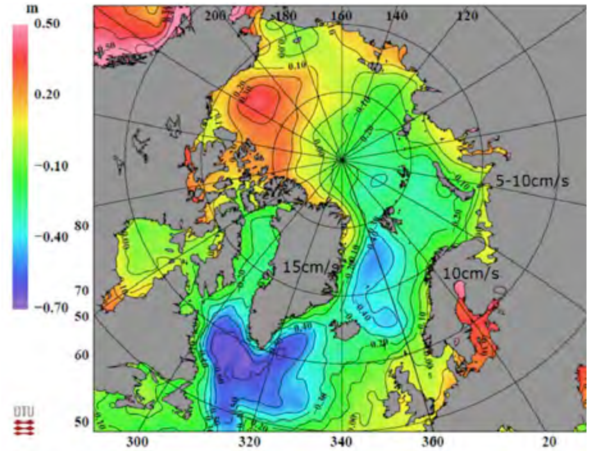


Figure 1. Mean dynamic topography in the Arctic based on a new estimate of the mean sea surface, minus an estimate of the geoid. The high sea level north of Canada illustrates the clockwise motion of the Beaufort gyre, a part of the wind-driven ocean circulation of the Arctic. **Image credit:** Ole Andersen

Because the shape of the sea floor exerts such a strong influence on the geoid, it is possible to use estimates of the geoid to derive the shape of the sea floor. In the same splinter session, **Walter Smith** [NOAA/Satellite Applications and Research (STAR), U.S.] showed how estimates of the sea floor shape, based on sea level measurements from the new AltiKa satellite, compare with direct, ship-based measurements of the sea floor shape—see **Figure 2**. AltiKa has very high along-track resolution; therefore, very small topographic features in the sea floor can be detected.

Science Results from Satellite Altimetry

Several presentations in this splinter session focused on reconciling sea level changes observed by altimeters with changes in ocean mass and *steric height*—sea level changes caused by changes in temperature and salinity. **Eric Leuliette** [NOAA/STAR] presented results showing the seasonal cycle of sea level change in the global ocean. Observations of ocean temperature and salinity from the Argo array of profiling floats, and observations of local ocean bottom pressure, or column-integrated ocean mass based on data from NASA's Gravity Recovery and Climate Experiment (GRACE), show excellent agreement with altimeter-based observations—see **Figure 3**, next page. This is an indication that seasonal sea level changes in the open ocean and their underlying causes are well understood.

Highlights from the Closing Plenary

In the closing session, participants heard summaries of each of the splinter sessions, as well as an overview of two other important meetings that took place recently. **Paolo Cipollini** [National Oceanography Centre, U.K.] reported on the Ninth Coastal Altimetry Workshop, and **Jérôme Benveniste** [ESA, Italy] summarized the Third Space for Hydrology Workshop, which took place in Frascati (Rome), Italy, September 15-17, 2015.

The meeting ended with an update on the status of reprocessing. **Phil Callahan** [JPL] discussed reprocessing for the Ocean Topography Experiment (TOPEX)/Poseidon mission and provided and update

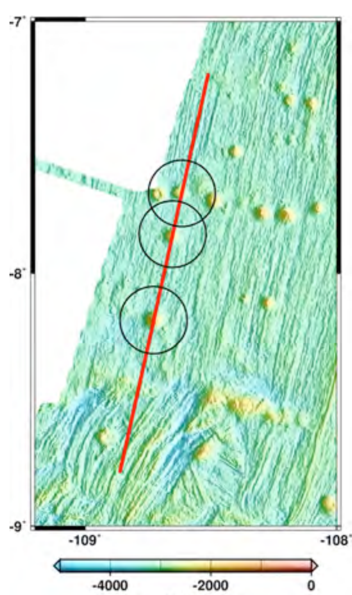
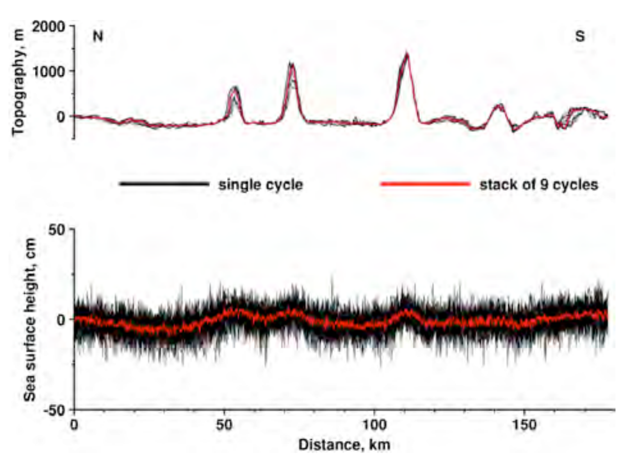


Figure 2. Sea floor depth [*left*] as measured during a ship-based survey. The red line shows a track from AltiKa that crosses three seamounts. The two plots show topography [*upper right*] and sea surface height [*lower right*] estimated from several passes of AltiKa, sampling at 40 times per second. The high sampling rate and K_a-band radar allow the sea floor shape to be accurately estimated down to a horizontal resolution of 10 km (~6.2 mi), after 9 passes. **Image credit**: Karen Marks [*left*] and Walter Smith [*right*]



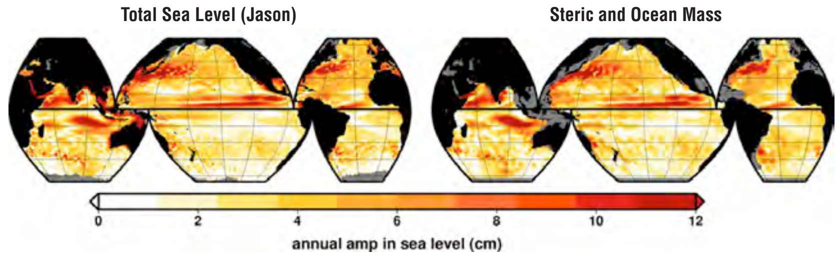


Figure 3. The amplitude of the annual cycle in sea level as observed by the Jason altimeters [*left*], and the sum of steric (density-related) and bottom pressure changes as observed by Argo and GRACE [*right*], respectively. Good agreement between these implies that seasonal changes in sea level are well measured by these three complementary observing systems. **Image credit:** Eric Leuliette

on geophysical data record (GDR[6])-C standards. He reported that retracted data has been generated, and evaluation of the revised data and the geophysical corrections is ongoing. **Nicolas Picot** [CNES] discussed current GDR status for Jason-1 and Jason-2. Three years of Jason-1 data are now available and have been processed to GDR-E standards. Plans to reprocess remaining Jason-1 and Jason-2 data to a new GDR-E standard are underway. For the calibration and validation phase, Jason-3 will be based on the GDR-D standards in all aspects except for the orbit, which will comply with GDR-E standards. This will make Jason-3 data products fully consistent with those from Jason-2. The next product version will be defined after the calibration and validation phase.

As a result of discussions held during the closing plenary session, the OSTST adopted the following recommendations:

- Although the mission has long since ended, data from TOPEX/Poseidon remain widely used in scientific studies and are a key part of the sea level climate data record. The OSTST recommends that the Jason projects continue to support efforts to bring TOPEX/Poseidon data in line with modern altimetry standards.

- In light of the need for improved mean sea surface estimates for SWOT in 2020 (between two and three years of observations are needed), the OSTST recommends that Jason-2 be moved to a geodetic orbit, preferably at a +35-km (~22-mi) altitude (12+247/401[7]), to support geodetic studies if and when it becomes feasible. Further study and consideration of future launches and the overall health of the altimeter constellation, by both the projects and the OSTST Jason-2 EOL subgroup, is recommended to find precise criteria for the timing of the move to a geodetic orbit.

- The Jason-2 Project should consider implementation of the radiometer calibration maneuver that will be implemented on Jason-3 in order to provide a cold-sky calibration look for the Advanced Microwave Radiometer (AMR) on Jason-2 after it has been successfully demonstrated on Jason-3.

- Airborne instruments have demonstrated the capabilities of high-frequency radiometers to provide improved corrections near land. Therefore, future altimetry missions should consider adding additional higher-frequency radiometer channels in order to improve coastal and inland water wet-path delay corrections.

- All altimeter missions should develop a plan to provide open, freely available, and up-to-date documentation of all processing techniques and project events for official releases of altimeter data, and to archive all relevant information at the end of each mission.

To close, the OSTST recognized and acknowledged several entities:

- The OSTST appreciates that CNES and NASA have nearly completed the Jason-1 reprocessing begun in 2013, and acknowledges the funding and support provided by CNES and NASA for this activity.

- The OSTST recognizes the high value of the new Jason-1 dataset for climate studies.

- The OSTST appreciates the Jason-3 Project's efforts to launch in a safe yet timely manner.

- The OSTST appreciates the work of CNES and ISRO to continue to provide high-quality data products for the SARAL/AltiKa mission[8], which is of great value for climate and operational oceanography activities.

Conclusion

The meeting fulfilled all its objectives. It provided a forum for an update on the status of Jason-2 and other relevant missions and programs, and detailed analyses of the observations by the splinter groups.

The OSTST will reconvene October 31–November 4, 2016, in La Rochelle, France. ■

[6] A geophysical data record (GDR) refers to a fully validated data product that uses precise orbital values and the best environmental/geophysical corrections. The -C, -D, and -E, refer to different releases, each using more updated processing techniques than the previous, to make the datasets more consistent.

[7] In this orbit the satellite will complete 12.6159601 (=12+247/401) revolutions per day and after 401 days, it will repeat along its original ground track.

[8] A special issue of *Marine Geodesy* highlighting this high quality data is now published at *www.tandfonline.com/toc/umgd20/38/sup1#.VimFdsuqjsI.*

ESIP Addresses Earth Sciences Big Data at its 2016 Winter Meeting

Rebecca Fowler, Federation of Earth Science Information Partners, rebeccafowler@esipfed.org

Introduction

The 2016 Federation of Earth Science Information Partners' (ESIP) Winter Meeting was held at the Marriott Wardman Park in Washington, DC, January 6-8. Nearly 300 attendees came together to discuss current trends, problems, and emerging issues affecting the field of Earth science informatics. The three days of plenary talks, breakout sessions, poster presentations, and technical workshops addressed the meeting theme: *Frontiers in Earth Sciences Big Data*. This theme was chosen for the 2016 biannual ESIP meetings and virtual collaboration initiatives in recognition of the importance of improving the use of Earth and space science *big data*—extremely large datasets that may be analyzed computationally to reveal patterns, trends, and associations. Some of the primary topics discussed at the Winter Meeting were how big-data technologies benefit Earth- and space-science research; the unique opportunities and challenges big data present for storage, management, and access technologies; and the volume, variety, veracity, and *velocity* (which, in this context, refers to the speed at which new information is generated and processed) of Earth-sciences big data. ESIP also selected its officers, representatives, and committee chairs at the Winter Meeting—see *New Leadership Elected,* below.

Full meeting proceedings are available at *commons.esipfed.org/2016WinterMeeting*. For a summary of recent and upcoming ESIP activities, see *ESIP News* on page 19.

Plenary Activities

Two lively plenary sessions spread over two days focused on the value of big data in various settings and applications, from climate modeling to humanitarian aid. Below is a summary of the plenary presentations and the topics they addressed. Each of the Winter Meeting plenary talks can be viewed at *bit.ly/1XtLz3B.*

Kerstin Lehnert [Interdisciplinary Earth Data Alliance, Lamont-Doherty Earth Observatory/Columbia University] discussed the value of *small data* and their contributions to Earth-science research. Lehnert encouraged the scientific community to focus on data value and not size, reasoning that when data, regardless of size, are properly curated, documented, harmonized, and integrated, they become a useful breeding ground for finding patterns and trends, and inspiring new ideas.

Gavin Schmidt [NASA's Goddard Institute for Space Studies (GISS)] spoke about the power of data to broaden the understanding of climate science and successfully mitigate the impacts of climate change.

New Leadership Elected

The ESIP Executive Committee is comprised of elected members, who govern ESIP's activities throughout the year. The new officers and committee chairs (listed below) took office on January 7, 2016.

***President,* Emily Law** [NASA/Jet Propulsion Laboratory]

***Vice President,* Christine White** [Esri]

***Constitution and Bylaws Committee Chair,* Ken Keiser** [University of Alabama in Huntsville]

***Data Stewardship Committee Chair,* Justin Goldstein** [U.S. Global Change Research Program]

***Education Committee Chair,* LuAnn Dahlman** [NOAA]

***Finance Committee Chair,* Bill Teng** [NASA's Goddard Space Flight Center]

***Information Technology and Interoperability Committee Chair,* Ethan Davis** [Unidata]

***Partnership Committee Chair,* Danie Kinkade** [Woods Hole Oceanographic Institution]

***Products and Services Committee Chair,* Soren Scott** [Ronin Institute for Independent Scholars]

***Semantic Technologies Committee,* Tom Narock** [Marymount University]

Schmidt argued that strategies such as enabling greater access to climate data and using them to tell compelling stories could move climate science out of its "research silo" to application in the larger world. As an example he demonstrated the GISS/Bloomberg global warming visualization, which can be viewed at *www.bloomberg.com/graphics/2015-whats-warming-the-world*.

Patrick Meier [Next Generation Humanitarian Technology and Robotics] gave an overview of unmanned aerial vehicles (UAVs), or *drones*, as a new source of big data that is of immense value for humanitarian applications. Meier's organization focuses on making these data available, accessible, and free to humanitarian organizations—work that is helping to revolutionize the effectiveness of relief efforts, worldwide.

Rafael Ameller [StormCenter Communications, Inc.] described his company's efforts to make big data and mapping platforms more relevant and useful on both mobile and traditional computing platforms during decision-making. StormCenter Communications' goal is to improve access to geospatial information to address the critical need for enhanced collaborative decision-making in emergency and crisis management.

Steve Adler [IBM] discussed the need for an Open Climate Data Repository, where weather and climate data could be properly inventoried, classified, managed, and retained. Adler called on ESIP community members to use their expertise in data management, data integration, climate data, and societal impacts to implement such a repository, ultimately to help reduce human vulnerability to environmental hazards.

Following the plenary presentations, there was a panel discussion that featured: **Jeff de La Beaujardière** [National Oceanic and Atmospheric Administration (NOAA)]; **Jeff Walter** [NASA]; and **Sky Bristol** [U.S. Geological Survey]. The three speakers gave presentations about big data in relation to their respective agencies' activities and initiatives. The discussion that followed focused on brainstorming ways that ESIP community members might contribute their skills and knowledge to improving use of such federal data.

ESIP News

Much has been happening in the ESIP community. Some of the more recent and upcoming highlights are provided here.

2016 ESIP Summer Meeting. The next meeting has been scheduled for July 19-22 in Chapel Hill, NC. The summer meeting is open to all and typically draws around 300 attendees from diverse Earth-, space-, and environmental-science backgrounds. The call for session proposals is open until April 1; sessions may be related to the meeting theme, *Frontiers in Earth Sciences Big Data*, or other topics relevant to the ESIP community. Visit *commons.esipfed.org/2016SummerMeeting* to learn more about the summer meeting.

GeoSpace Blog. To highlight and share stories about the importance of Earth- and space-science data, ESIP now has a regular feature on the American Geophysical Union's (AGU) blog, *GeoSpace*. Posts in this series, found at *blogs.agu.org/geospace/category/data,* showcase data facilities and data scientists; explain how Earth- and space-science data are collected, managed, and used; explore what these data tell us about the planet; and delve into the challenges and issues involved in managing and sharing data. Guest authors and topic suggestions for posts are welcome; contact *rebeccafowler@esipfed.org* to discuss ideas.

Ignite at AGU. ESIP, NASA's Applied Sciences Program, and AGU's Earth and Space Science Informatics Section once again sponsored this popular science storytelling event at the 2015 AGU Fall Meeting. Ignite enables scientists to showcase their professional and personal interests through fast-moving, creative presentations. Four of the 13 presenters were from NASA field centers; you can view the full list of speakers and watch their presentations at *esipfed.org/IgniteAGU2015*.

Science Communication Cluster. This new group is devoted to improving public communication of science, and aims to advance broad scientific understanding of Earth- and data-science by providing a forum for discussion and resource development. Anyone interested in science communication is welcome to join the cluster; visit *wiki.esipfed.org/index.php/Science_Communication* to learn more.

ESIP Monday Update. This weekly email summarizes recent ESIP news and upcoming activities of interest, such as workshops, telecons, funding, and job opportunities. Visit *esipfed.org/esip_recent-news* to subscribe to the ESIP Monday Update.

Five New Member Organizations Welcomed into ESIP

Five new member organizations were accepted into ESIP at the meeting—see **Table**. These new additions brought the organizational membership total to 180. Membership is divided into three categories: data providers (*Type I*), researchers (*Type II*), and application developers (*Type III*). Membership in ESIP is voluntary, and open to organizations that work at the intersection of Earth science data and supporting technologies. Among the benefits of participating in ESIP are exposure to new technology and emerging concepts in Earth science data, professional development opportunities, and the opportunity to network with colleagues from the Earth-science informatics community.

Table. New member organizations accepted at the 2016 ESIP Winter Meeting.

Member Organizations	Member Category
American Geophysical Union (AGU)	Type II
Consortium of Universities for the Advancement of Hydrologic Science (CUAHSI)	Type I
Data Semantics (DaSe) Laboratory at Wright State University	Type II
U.S. Department of Agriculture's National Agricultural Library (NAL)	Type I
Northwest Knowledge Network (NKN)	Type III

ESIP Recognizes Community Leaders

Three leaders in the field of Earth-science information were honored at the Winter Meeting.

Ruth Duerr [Ronin Institute for Independent Scholars] received the *Martha Maiden Lifetime Achievement Award for Service to the Earth Science Information Community*. This award, named for Martha Maiden, NASA's Program Executive for Earth Data Systems, honors individuals who have demonstrated leadership, dedication, and a collaborative spirit in advancing the field of Earth-science information. Duerr served as the founding chair of the ESIP Data Stewardship Committee and helped grow that committee out of the earlier ESIP Preservation and Stewardship cluster, which she also led.

Denise Hills [Geologic Survey of Alabama] was honored with the *President's Award* in recognition of her considerable contributions to ESIP in 2015. Former ESIP President **Peter Fox**, who selected Hills for the award said, "The impact of Hills' involvement is significant. ESIP now has vibrant new leadership as a result of her work."

ESIP 2016 award recipients with **Martha Maiden**. [*Left to right*] **Denise Hills**, **Ruth Duerr, Martha Maiden,** and **Soren Scott**. **Image credit**: Bruce Caron

Soren Scott [Ronin Institute for Independent Scholars] received the *Catalyst Award*. This award recognizes individuals who have brought about positive change in ESIP and inspired others to take similar action. Scott quickly revitalized several informal ESIP working groups, including the Web Services and Semantic Web Clusters, which had become dormant due to a lack of community involvement and guidance.

Conclusion

The knowledge and expertise of ESIP members gives the organization a unique capacity to provide practical solutions to the challenges related to Earth-observations data. Much of the work ESIP members undertake is done in a virtual and distributed way, but bringing the community together for the biannual meetings builds and sustains ESIP, creates new collaborations, and advances projects and initiatives that serve the entire Earth-data science community. This work continues to result in improved Earth-science data management practices and make Earth-science data more discoverable, accessible, and useful to researchers, policy makers, and the public.

In a summary statement, **Emily Law**, the newly elected ESIP President, said, "ESIP meetings are a vital part of our community, where members and nonmembers learn, network, and create exciting new collaborations. With so many knowledgeable presenters and a record-breaking number of attendees at the 2016 Winter Meeting, there was an endless supply of fresh ideas and energy that will help move the field of Earth-data science forward in the coming years." ■

2015 CLARREO Science Definition Team Meeting Summary

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Rosemary Baize, NASA's Langley Research Center, rosemary.r.baize@nasa.gov
Bruce Wielicki, NASA's Langley Research Center, bruce.a.wielicki@nasa.gov

Introduction

The eighth meeting of the Climate Absolute Radiance and Refractivity Observatory (CLARREO) Science Definition Team (SDT) was held at the National Institute of Aerospace (NIA) in Hampton, VA, December 1-3, 2015. Over 25 investigators participated in the meeting, which included 26 presentations. Attendees were from NASA Headquarters (HQ), NASA's Langley Research Center (LaRC), NASA's Goddard Space Flight Center (GSFC), NASA/Jet Propulsion Laboratory (JPL), University of Wisconsin, Harvard University, University of Michigan, Lawrence Berkeley National Laboratory, Science Systems and Applications, Inc., McGill University, and Imperial College in London.

The meeting objectives were to discuss progress made for the CLARREO Pathfinder Mission; report on science, project, and engineering progress for the Infrared (IR), Reflected Solar (RS), and Radio Occultation (RO) instruments; discuss the newly released National Research Council (NRC) Continuity Report and plans to support the next NRC Decadal Survey[1]; and relay the status of international collaboration efforts for CLARREO.

A few of the highlights from the presentations given at the meeting are summarized below. Many of the presentations can be viewed online at *clarreo.larc.nasa.gov/events-STM2015-12.html*.

[1] For more information, visit *science.nasa.gov/earth-science/decadal-surveys*.

Meeting Highlights

Refining Climate Change Calibration Accuracy Requirements

Yolanda Shea (*née* Roberts) [LaRC] highlighted important progress made on science-driven climate change accuracy requirements. Specifically, Shea's presentation addressed how to define climate-observing system requirements, determine the impact of instrument measurement uncertainty on detection time, and quantify the impact of algorithm uncertainty on detection time. She noted that the length of time required to detect a climate trend caused by human activities is dependent on three factors: natural variability, human-driven climate change magnitude, and observing system accuracy. Shea and her colleagues are expanding such accuracy framework studies to include additional essential climate variables—specifically, Shea discussed cloud properties. Having a clear understanding of how observed cloud properties change over time is a requirement for constraining the cloud feedback differences among climate models. Because small changes in cloud properties need to be detected to understand the role of clouds in Earth's changing climate, both the cloud property retrieval algorithms and satellite instruments used to monitor clouds must be subject to stringent accuracy requirements.

To achieve these levels of decadal-scale accuracy requires CLARREO reference intercalibration with cloud imagers such as the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard NASA's Aqua and Terra missions and Visible Infrared Imaging

Attendees at the CLARREO SDT Meeting in Hampton, VA. **Photo credit**: George Homich

Radiometer Suite (VIIRS) onboard the Suomi National Polar-orbiting Partnership (NPP) mission. Using MODIS data and the CERES Cloud Property Retrieval System, Shea was able to show that for a MODIS-like RS instrument to detect trends in cloud optical thickness with trend accuracy within 20% from that of a hypothetical "perfect" instrument (with 0% calibration uncertainty and only limited by natural variability), it would need an accuracy requirement similar to that of the current CLARREO RS instrument—see **Figure 1**. Her work also linked accuracy requirements to the Coupled Model Intercomparison Project Phase 5 (CMIP5) equilibrium climate sensitivity (ECS) intermodel range, illustrating how CLARREO-like reference intercalibration could help constrain our understanding of this value. After publishing the results from this study, follow-on studies will be performed that evaluate accuracy requirements considering the calibration accuracy in multiple spectral bands simultaneously; evaluating requirements by cloud type; and extending the analyses to MODIS Science Team cloud algorithms and VIIRS.

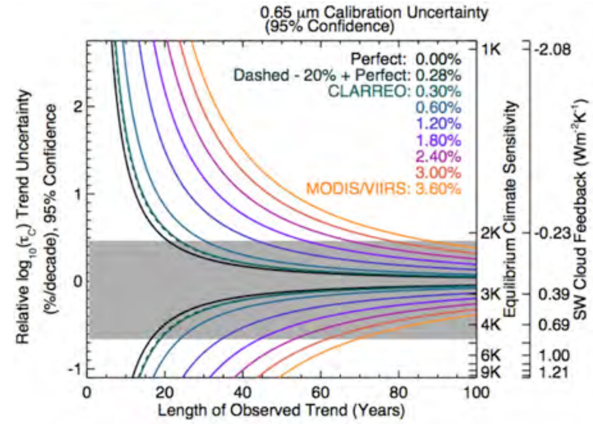

Figure 1: The estimated time (x-axis) it would take to begin distinguishing a secular relative cloud optical thickness trend (left y-axis) from natural variability is shown here linked to the SW Cloud Feedback and the equilibrium climate sensitivity (right y-axes). Linking these three quantities provides the approximate range of cloud optical depth trends to be expected for the intermodel range of CMIP5 ECS (shaded in gray). The CLARREO reflected solar accuracy requirement of 0.3% (k = 2), is nearly equivalent to the accuracy of an instrument capable of detecting an optical thickness trend with an accuracy within 20% of that of a perfect instrument (dotted curve). **Image credit**: NASA LaRC

Options for Location of CLARREO Pathfinder on ISS

Previous studies (from 2012) explored the possibility of attaching CLARREO to the Japanese Experiment Module (JEM; also known as *Kibo*), which is onboard the International Space Station (ISS). The JEM site was specifically chosen for design studies due to its field-of-regard, mass, power, and thermal management capabilities. The team concluded that because of the higher reliability of the ISS as a spacecraft, thereby allowing a longer climate record, this option offers the best overall science value of 73% for the lowest cost. Due to the 52° inclination of the ISS orbit, CLARREO will not have coverage of Earth's polar regions; however, flying in a precessing orbit will significantly enhance sampling for intercalibration of existing sensors.

Following that study, **Costy Lukashin** [LaRC], **Carlos Roithmayr** [LaRC], and **Craig Hutchinson** [LaRC] examined the challenges of conducting RS intercalibration sampling from two alternate locations on ISS.

Subsequent analysis showed that sites 3 and 8 onboard the Express Logistics Carrier 1(ELC-1) were optimal—see **Figure 2**. Specifically, to conduct a simulation of obscuration from the two sites on the ISS, Hutchinson modeled the RS instrument on ISS within the Satellite Tool Kit (STK). Using the STK tool, the percentage of obscuration of the sensor's field of view by the ISS was captured as a fixed and rotating structure over the course of the period of analysis. Preliminary results indicate that site 8 provides more non-obscured intercalibration opportunities and can meet the CLARREO accuracy requirements better than site 3.

CLARREO Pathfinder: A Stepping Stone to the Complete Mission

Rosemary Baize [LaRC] delivered an overview of the benefits, progress made, and plans to move forward on the CLARREO Pathfinder mission on the ISS. As a

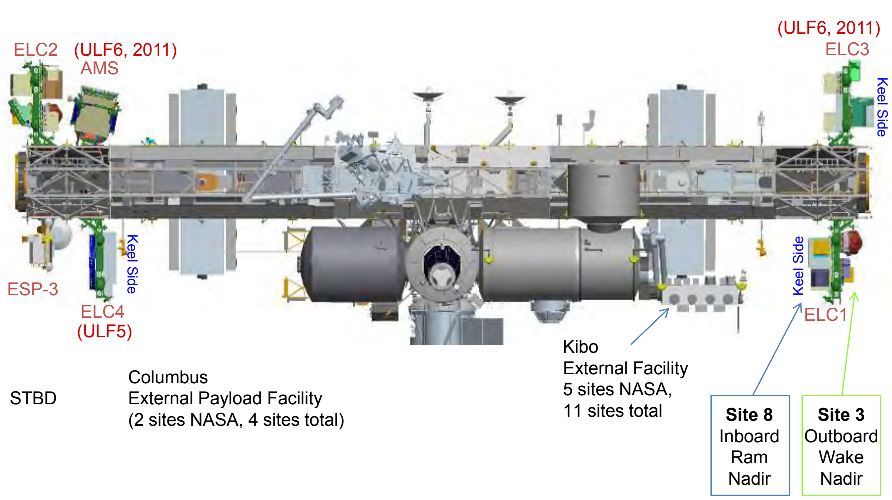

Figure 2: The ISS, with emphasis on Express Logistics Carrier (ELC)-1 sites 3 and 8. Preliminary results indicate that site 8 provides more non-obscured intercalibration opportunities and can meet the CLARREO accuracy requirements better than site 3. Note that in this diagram, the JEM is labeled with its nickname, *Kibo*. **Image credit:** NASA GSFC

Class D Mission[2], CLARREO Pathfinder is not the complete CLARREO mission. Instead, the objective of this Pathfinder mission is to reduce risk and demonstrate the new capabilities CLARREO would present once in orbit.

Benefits of the Pathfinder that will contribute to the success of the future CLARREO mission include the ability to:

- reduce risk/provide confidence that the full CLARREO mission can achieve its science goals;
- demonstrate higher-accuracy calibration approaches;
- prove that high climate change accuracy and Système international d'unités (SI)-traceability can be transferred to orbit;
- show that high-accuracy intercalibration is achievable;
- provide the first on-orbit SI-traceable reflectance with uncertainty <0.5% (k=2);
- provide the first on-orbit SI-traceable temperature with uncertainty <0.07 K (k=2); and
- demonstrate the new far-infrared observation capability that is key for verification of the water vapor greenhouse effect and water vapor feedbacks.

Further, Pathfinder will contribute to many other existing and future NASA Earth science missions by:

- improving laboratory calibration approaches;
- developing and testing innovative, on-orbit, SI-traceable methods;
- transferring calibration to sensors in operation at time of CLARREO Pathfinder; and
- improving lunar irradiance standards.

Some Pathfinder Limitations

The CLARREO Pathfinder does have several limitations when compared to the full CLARREO mission.

- The relatively short planned lifetime of the CLARREO Pathfinder (one year at 85% and two years at 70% reliability) will likely result in a record shorter than the five years of observations needed to begin the CLARREO full-mission spectral fingerprint benchmarks (Level 2 and Level 3 data products).
- The Pathfinder budget will support full Level 0 processing[3], but only limited Level 1—and no Level 2 and 3—processing. Observations deemed necessary to demonstrate the calibration accuracy and intercalibration capability will be processed to Level 1.
- Level 4 processing is limited to that sufficient to demonstrate intercalibration for the Clouds and the Earth's Radiant Energy System (CERES) onboard Terra, and VIIRS and the Cross-track Infrared Sounder (CrIS) onboard Suomi NPP.
- If Pathfinder is judged highly successful, meaning that the team has advanced the technology development and delivered useful science, NASA HQ may decide at a later time to fund processing of the Pathfinder Level 0 observations to provide the full CLARREO mission Level 1 through Level 4 data products.
- Global Navigation Satellite System-Radio Occultation (GNSS-RO) observations are not obtained on ISS.

Next Steps and Moving Forward

The meeting concluded with a discussion of the "next steps" that the CLARREO SDT needs to take. These included generating a plan to form a Pathfinder Mission Project Team; finalize approval of Class D implementation approaches with management at LaRC, and the Earth Science Mission Program Office (ESMPO), and the Earth Science Division (ESD) at NASA HQ; and complete accommodation feasibility studies for both instruments (IR and RS) on the ELC-1 in cooperation with appropriate ISS personnel. The group also discussed the need for a continued effort to advance relevant science by publishing key journal papers on CLARREO orbit sampling, IR and RS intercalibration sampling, Instrument Incubator Program and Calibration Demonstration System calibration methods and accuracy levels, and the economic value of higher-accuracy climate observation missions—such as CLARREO. At the close of the meeting, the group declared that they would like to host a discussion with members of the observation and climate modeling communities to discuss strategic planning efforts for observations needed to improve climate models.

The next CLARREO SDT Meeting is scheduled to take place at the University of Michigan in Ann Arbor, MI, May 10-12, 2016. ■

[2] A *Class D* mission is considered low priority with regard to NASA's strategic plan; low-to-medium in terms of national priority; medium-to-low in complexity; with lifetime of less than two years. Full details on risk classifications for NASA payloads can be found in *Appendix B* of the NASA Procedural Requirements (NPR) document 8795.4: *nodis3.gsfc.nasa.gov/npg_img/N_PR_8705_0004_/N_PR_8705_0004_.pdf.*

[3] For descriptions of the various Data Processing Levels set by the NASA's Earth Observing System Data and Information System (EOSDIS), please refer to *science.nasa.gov/earth-science/earth-science-data/data-processing-levels-for-eosdis-data-products.*

ECOSTRESS Science Team Meeting

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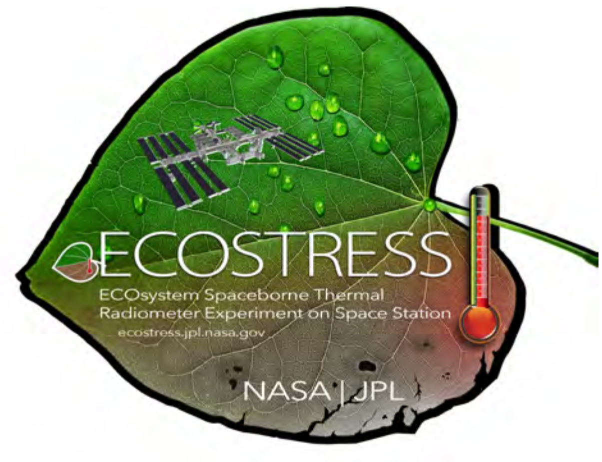
Introduction

The ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS) mission is one of two instruments chosen from the second Earth Venture Instrument (EVI-2) Pathfinder Program Announcement of Opportunity (AO)[1]. With a launch currently scheduled for 2018, ECOSTRESS will assess vegetation water stress using a multispectral thermal instrument installed on the International Space Station (ISS). ECOSTRESS will orbit between 385 km (~239 mi) and 415 km (~258 mi) above Earth's surface at a 51.6° inclination, with a nearly three-day repeat cycle. It will provide about a 60-m (~197-ft) spatial resolution. Due to the unique orbital path of the ISS, ECOSTRESS will observe the same spot on Earth at different times each day. This configuration will enable an unprecedented view of diurnal trends in vegetation evapotranspiration, allowing the science community to address the following questions:

- How does the terrestrial biosphere respond to changes in water availability?
- How do evapotranspiration and vegetation water stress interact with the global carbon cycle?
- How can scientists better understand agricultural vulnerabilities and drought impacts linked to vegetation water stress?



Science Team Meeting Summary

The second ECOSTRESS Science Team Meeting took place in Washington, DC, November 5, 2015[2]. Attendees included representatives from the ECOSTRESS Science Team: **Simon Hook** [NASA/Jet Propulsion Laboratory (JPL)—*ECOSTRESS Principal Investigator*], **Joshua Fisher** [JPL—*Science Lead*], **Glynn Hulley** [JPL], **Martha Anderson** [U.S. Department of Agriculture (USDA)], **Chris Hain** [National Oceanic and Atmospheric Administration (NOAA)], **Andrew French** [USDA], **Rick Allen** [University of Idaho], and **Eric Wood** [Princeton Uninversity]. Also present were **Ben Bornstein** and **Tom Logan** [both from JPL], who represented the ECOSTRESS Data System, **Christine Lee** [JPL—*Applications Lead*], **Chris Doescher** [U.S. Geological Survey's (USGS) Earth Resources Observation and Science (EROS) Data Center/NASA's Land Processes Distributed Active Archive Center (LP DAAC)], **Liang Sun** and **Yang Yang** [both from USDA], **Hank Margolis** [NASA Headquarters (HQ)—*Terrestrial Ecology Program Manager*], **Jared Entin** [NASA HQ—*Terrestrial Hydrology Program Manager*], **Woody Turner** [NASA HQ—*ECOSTRESS Program Scientist*], and **Sarah Hemmings** [NASA HQ—*Applied Sciences*].

The agenda included a series of presentations that focused on the planned ECOSTRESS data products. **Tom Logan** provided an overview of the Level 1 radiance and geolocation data, and **Glynn Hulley** discussed Level 2 land surface temperature and emissivity data production.

Joshua Fisher and **Martha Anderson** reviewed two of the three planned Level 3 *evapotranspiration* (ET) data products for ECOSTRESS; ET is comprised of evaporation of water from Earth's surface along with the amount of water that plants transpire. Fisher described an algorithm that uses the Priestley–Taylor-Jet Propulsion Laboratory (PT-JPL) method for determining ET, while Anderson described another approach, developed at USDA, based on two-source energy-balance calculations for determining evapotranspiration called the Atmospheric Land EXchange Inversion (ALEXI) algorithm.

continued on page 30

[1] The Science Mission Directorate (SMD) at NASA Headquarters selected two proposals from among those submitted in response to the Second Stand Alone Mission of Opportunity Notice (SALMON-2), Program Element Appendix (PEA) M: Earth Venture Instrument-2, *NNH12ZDA0060-EVI2.* The other successful proposal was the Global Ecosystem Dynamics Investigation (GEDI).
[2] Additional background on ECOSTRESS may be found in the summary of the first ECOSTRESS Science Team Meeting in the May–June 2015 issue of *The Earth Observer* [**Volume 27**, **Issue 3**, pp. 28-29].

2015 GRACE Science Team Meeting

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The Gravity Recovery and Climate Experiment (GRACE) mission entered its fourteenth year on March 18, 2015. A joint endeavor between NASA and the Deutsches Zentrum für Luft-und Raumfahrt (DLR) [German Aerospace Center], the twin GRACE satellites continue to improve our understanding of Earth's dynamical nature, making precise measurements of changes in the gravity signals associated with exchange of mass between several Earth-system components. The 2015 GRACE Science Team Meeting (GSTM) took place September 21-23, 2015, at the Center for Space Research (CSR), in Austin, TX. More than 100 scientists and engineers attended the meeting, which consisted of 91 oral presentations distributed across the 7 science sessions, as described in this report.

Opening Remarks and Programmatic Updates

After host **Byron Tapley** [University of Texas at Austin (UT)/CSR—*GRACE Principal Investigator*] welcomed the participants, he began with a formal presentation on the status of and prospects for the GRACE mission. The mission has produced 146 *Release-05* (RL05) monthly measurements of Earth's gravity field (out of a maximum possible 160[1]) that are improved by approximately a factor of two over the previous *Release-04* product. Tapley highlighted that the 2015 NASA Senior Review has extended the GRACE mission to 2019, and that operations are focused on extending mission life for overlap with the GRACE Follow-On (GRACE-FO) mission, to be launched in 2017.

Several programmatic presentations came next:

- **Mona Witkowski** [NASA/Jet Propulsion Laboratory (JPL)] reviewed GRACE flight operations and satellite health. In particular, she mentioned that the spacecraft battery operations require regular monitoring and management, to maximize the satellite's lifetime.
- **Gerhard Kruizinga** [JPL] reviewed the status of GRACE Level-1 processing at JPL.
- **Srinivas Bettadpur** [UT/CSR], **David Wiese** [JPL], and **Christoph Dahle** [GeoForschungsZentrum (GFZ)] reviewed the status of the latest Level-2 products produced by UT/CSR, GFZ, and JPL, respectively.
- **Rob Gaston** [JPL—GRACE *Project Manager*] and **Himanshu Save** [UT/CSR—*GRACE Assistant Science Operations Manager*] gave an overview of the health of the satellite and its various subsystems and current operations.
- **Michael Watkins** [UT/CSR—*GRACE-FO Science Team Lead*] presented a status update on the GRACE-FO mission.
- **Bradley Dorn** [NASA Headquarters—*GRACE-FO Applications Lead*] introduced the GRACE-FO Applications Program.

Science Sessions

The remainder of the meeting comprised seven science sessions:

- GRACE Analysis Techniques;
- GRACE-FO and Bridging the Gap;
- Multidisciplinary Science;
- Solid Earth Science;
- Cryosphere;
- Hydrology; and
- Oceanography.

Each session included a series of invited and contributed presentations and a closing period for questions and answers. In addition, posters relevant to each topic were displayed for discussion throughout the meeting.

Group photo of 2015 GSTM attendees.

[1] To save energy, the instruments onboard the GRACE satellites are turned off and on, on a regular cycle. This leads to data gaps, and hence there are only usable data for 146 out of the 160 months that GRACE has been in orbit. The improvements are a natural evolution of satellite data releases and mainly due to improvements in the background models.

The GSTM program, abstracts, and the presentations are available at *www.csr.utexas.edu/grace/GSTM*.

GRACE Analysis Techniques

Two presentations addressed GRACE data analysis methods and algorithms that address the problem of reducing the noise in the gravity estimates. With different filtering strategies being made available, the uncertainties in the monthly estimates can be better quantified. An additional presentation demonstrated techniques to statistically better quantify trend estimates in GRACE data through the use of Kalman filtering.

The remaining two presentations focused on different approaches to produce *mascon*[2] *solutions* that, when compared to *spherical harmonic solutions*, employ physical constraints and regularization to constrain the monthly gravity fields and reduce noise.

GRACE-FO and Bridging the Gap

The session began with an overview of the GRACE-FO project status, including the flight system, payload, and ground system. The next presentation described the use of a land-surface hydrology model for assimilating GRACE-FO data, followed by one that assessed the geophysical aliasing errors expected for the mission. After that came a comparison of analytical methodologies, which suggests that aliasing is likely to remain a limiting factor for the foreseeable future. The next presentation provided new gravity results from Global Position Satellite (GPS) tracking of the European Space Agency's three Swarm satellites (the fifth Earth Explorer mission), possibly indicative of GPS-only gravity field quality should GRACE fail or partially fail before GRACE-FO is launched. There was also a presentation on the status of the GRACE-FO accelerometer, including the new performance and schedule with the design change from the gold wire used for GRACE to the 6.5-µm platinum wire. (The gold wires are no longer available, thus the change to platinum.) The last presentation in the session provided GFZ's latest projection of expected geoid errors from the Laser Ranging Interferometer (LRI) system on GRACE-FO.

Multidisciplinary Science

The multidisciplinary session opened with a discussion about the use of global GPS measurements and ocean bottom pressure (OBP) derived from model runs to assess accelerations in mass change related to ice, ocean, and hydrology variability. In their assessment of these runs, one presenter noted a reversal in acceleration for the Alaskan glacier and hydrological system. Another presentation reported on an investigation of the impact of self-attraction and loading (SAL) on Earth rotation. The study involved making estimates of mass loads on the surface of the Earth and their influence on pole position at monthly and interannual time scales. These results indicated that hydrological models are deficient in their representation of the excitation functions for polar motion, with respect to that derivable directly from GRACE. Comparison of mass balance calculated using traditional techniques excluding the SAL effect with one derived using SAL, revealed that inclusion of SAL is critically important for proper analysis of polar motion at interannual time scales.

Solid Earth Science

The first presentation in the Solid Earth session discussed the observation and modeling of the magnitude (M_w) 8.3 Sea of Okhotsk Earthquake that occurred on May 24, 2013; this study focused on the prospects of detecting the coseismic and postseismic signals from *deep-focus earthquakes* that occur near the major phase transition zones in the mantle in both GRACE and GRACE-FO data. Apparently, the signal originates from a very deep rupture beneath the Sea of Okhotsk, yet appears in the GRACE monthly solutions—even though the satellite pair recording the intersatellite range is about 1000 km (~621 mi) above the epicenter. Finally, there was a presentation on the importance of broad-scale, post-seismic motions that either have been observed or are currently under study, using GRACE data for as many as eight *great interpolate earthquakes* ($8.1 \le M_w \le 9.2$). The importance of the persistent postseismic motions is that these induce a gradual (as opposed to step-jump) change in the mass in the crust-mantle system; therefore, they are a scientifically important source for understanding tectonics and as a source for corrupting inferences of ocean or hydrological mass changes. The research again points to the need to observe and model great earthquakes for GRACE and GRACE-FO associated with $M_w > 8$, and especially as the energy liberated in the event corresponds to $M_w > 8.8$, regardless of the depth in the mantle.

Cryosphere

The cryosphere session included presentations that addressed improvements in techniques for deriving mass trends (and accelerations) and their error estimates. There was a presentation that demonstrated the utility of satellite laser ranging to extend large-scale gravity signals stemming from Greenland ice mass change back into the past and also the potential and limitations to continue them into the future. The next presentation gave an analysis of the local to regional contributions of surface mass balance (SMB) change to the GRACE signal and the potential of using GRACE to constrain SMB models particularly on long time scales where models are currently poorly constrained. Another presentation showed the regional impacts of ice sheet mass loss on sea level change due to changes in self-gravitation and loading. The authors of this study found that the regional distribution of ice loss can have a significant impact on oceanic sea level. The next two presentations

[2] A *mascon* is a localized mass concentration.

gave updated estimates of Canadian Archipelago glacier and Greenland ice loss and the Alaskan glacier system, respectively; both presentations included comparison with current climate model estimates. There was also a detailed analysis of the JPL mascon estimate of local Greenland ice loss in comparison with the Ice Sheet System Model. The comparison allows deriving conclusions about the relative contributions of errors in both models of SMB and ice dynamics. Another presentation gave an analysis of the 2013 slow-down of the Greenland melt and its causes, using a combination of GRACE and GPS data. Another report presented an analysis of the effects of errors in atmospheric background models on monthly gravity solutions over Greenland and Antarctica. Concluding the session was a presentation that provided a comparison between GRACE data on Greenland and Antarctic mass loss and data derived through other methods like satellite altimetry and the mass budget method showing some agreement between data from the different measurements, which can be used to assess the error for each method.

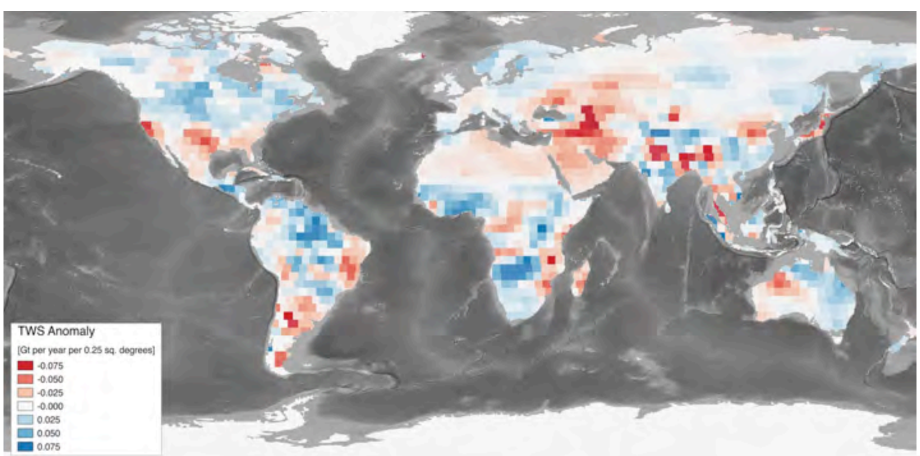
Hydrology

The hydrology session focused on advances in hydrology applications for GRACE data products, including signal interpretation, model assimilation, hydrological trends, long-term water storage variations, and terrestrial water balance decomposition. The session opened with a presentation on GRACE record-length land hydrology trends and their influence on global mean sea level using the new JPL RL05m mascon solution—see **Figure**.

The second presentation addressed recent advances in regional and global data assimilation using the NASA Land Information System (LIS) and Global Land Data Assimilation System (GLDAS) frameworks. Other presentations addressed climate applications for GRACE. These included models and observations of drought, groundwater depletion, structural improvement of the Community Land Model (CLM), terrestrial water balance trends, atmospheric model synergies with GRACE, and analysis of GRACE with auxiliary observations, such as *in situ*, Phased Array type L-band Synthetic Aperture Radar (PALSAR), and altimetry data. There were also two talks on signal-processing experiments for high-temporal-frequency (i.e., submonthly) signal capture.

Several major themes arose from these presentations:

- GRACE solution accuracy continues to improve with continued updates and new releases. These improvements, combined with a longer record length, enable many new science results. New GRACE mascon solutions provide a means to use GRACE for hydrology applications with smaller requirements for postprocessing signal recovery.
- Spatial downscaling is still a major research frontier for GRACE in the hydrologic sciences. Assimilation into a land-surface model seems to be the most viable of these techniques, and has already shown utility for regional-to-global drought monitoring.



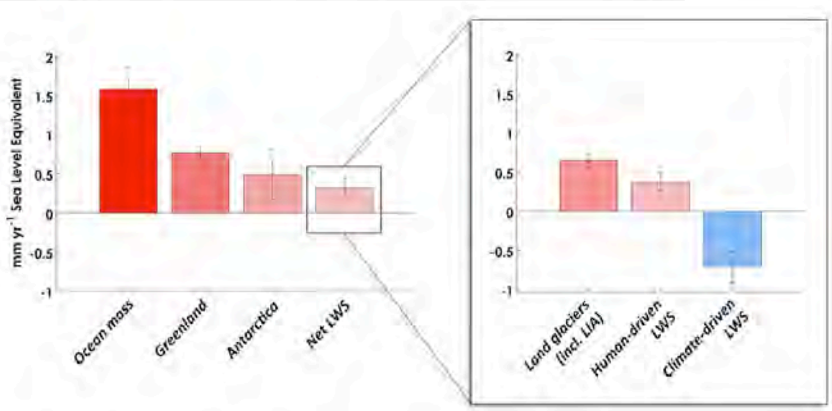


Figure [*Top*] Trends in land water storage (LWS) from 12.5 years of GRACE observations. (Totals exclude contributions from glaciers and ice sheets.) Red shades indicate increasing LWS, while blue shades indicate decreasing LWS. [*Bottom*] Global mass contributions to sea level from the ocean, ice sheets in Greenland and Antarctica, and Net LWS. [*Inset*] Net LWS is broken into its component parts, i.e., separating out the amount of LWS change that results from land glaciers, human activity, and climate. **Image credit:** John Reager

- Temporal variability within the monthly period is generally desired for some hydrology applications; there may be ways to extract that information from low-level GRACE data products.
- The accurate disaggregation of the "natural" and "anthropogenic" portions of GRACE terrestrial water storage anomaly trends continues to improve with improved analysis of *in situ* observations and land-surface model structural improvements.

Oceanography

The oceanography session covered topics including global and regional sea level budgets, barotropic and baroclinic ocean motions, tides and currents, and contributions of ocean circulation to polar motion, ranging in frequency from semidiurnal (tides), to 30–60-day oscillations, to decadal time scales.

With the improved gravity solution (RL05), and in particular with mascon-fields, novel applications of ocean current analysis were discussed: GRACE OBP variations can now be used to resolve variability in deep-ocean circulation at global scales, estimate Southern Ocean transport variations, and constrain Indonesian throughflow variations. They have also been demonstrated to accurately and independently observe the Atlantic Meridional Overturning Circulation.

New work on global and regional sea-level budgets reveals the depths into which ocean warming is penetrating, as well as the contributions of ocean warming and land ice changes to the global sea-level budget. Land-water storage changes over land were estimated to provide a more accurate quantification of Arctic river basin discharge, and the possible impact on regional ocean dynamics.

GRACE-observed time-variable OBP fields were evaluated for assimilation into ocean models, and used to reveal ocean regional dynamics in the Canadian Inland Seas. Time-mean fields from GRACE continue to improve mean sea-surface models.

Conclusion

Even though GRACE has long since exceeded its design lifetime, the mission continues to deliver extended data records of global mass redistribution for continued use in all Earth-science disciplines. The multinational mission operations team at German Space Operations Centre (GSOC), GFZ, JPL, and UT/CSR, together with industry support, continues to work towards minimizing the data gap that may occur before GRACE-FO continues these measurements into the next decade.

The next GSTM will be held in Potsdam, Germany, October 5–7, 2016. ■

GES DISC Announces Giovanni Image Hall of Fame Selections

The NASA Goddard Earth Sciences Data and Information Services Center (GES DISC) recently announced twelve new images selected for the Second Class of the Geospatial Interactive Online Visualization ANd aNalysis Infrastructure (Giovanni) Image Hall of Fame. To view the images, read the February 2016 issue of *The Giovanni News* at *disc.sci.gsfc.nasa.gov/giovanni/additional/newsletters*. The source of each image is described there, along with the primary reasons for the selection. Certificates noting the selection were sent to the first author of the research paper containing the image, or to the creator of the image.

For submissions to the Hall of Fame, Giovanni users were encouraged to employ the system to create new images. Papers published over the past two years were also reviewed for eligible images, either made using Giovanni directly, or created with data acquired through the use of Giovanni. The GES DISC selected an initial group of images, which were then provided to the public for voting via several user mailing lists; Earth scientists from NASA's Goddard Space Flight Center were also contacted directly and asked to vote. The most popular and most striking images were also further vetted for science content and visualization impact to produce the final selections.

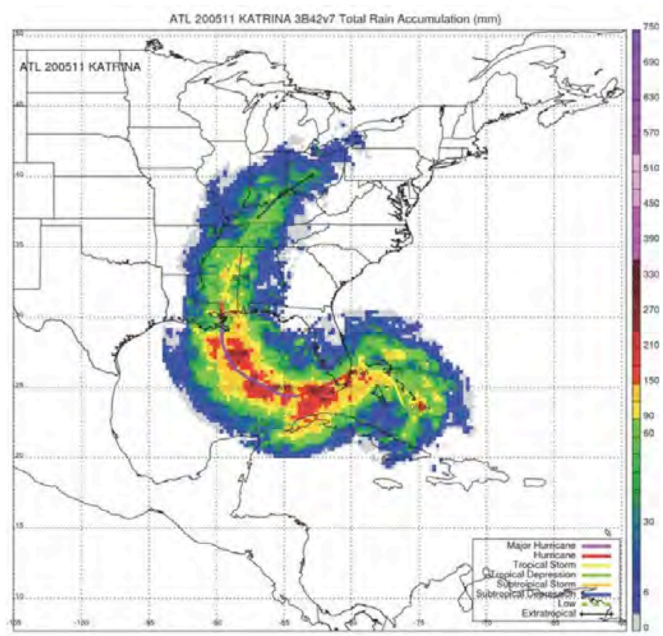
Giovanni allows access to a wide variety of NASA Earth science data products. Giovanni allows users to visualize data in several different ways, including time-averaged data maps, area-averaged time-series, x-y scatter plots, and Hovmöller plots.

Congratulations to the new class of Giovanni Image Hall of Fame selectees!

GHRC Becoming NASA's Hazardous Weather Distributed Active Archive Center

The Global Hydrology Resource Center (GHRC), one of NASA's twelve Distributed Active Archive Centers (DAACs), is responsible for providing access to NASA's Earth science data to users worldwide. Established in 1991 as NASA's Marshall Space Flight Center DAAC and renamed GHRC in 1997, the data center's original mission focused on the global hydrologic cycle. In response to the research community's evolving needs, the DAAC's mission is changing. Its new goal is *to provide a comprehensive active archive of both data and knowledge augmentation services with a focus on hazardous weather, its governing dynamical and physical processes, and associated applications*. Within this broad mandate, GHRC[1] will focus on lightning, tropical cyclones, and storm-induced hazards through integrated collections of satellite, airborne, and *in situ* datasets.

In keeping with its new focus, the GHRC DAAC team has developed a prioritized list of potential new datasets based on relevance to NASA's science objectives in extreme weather and weather hazards, to be evaluated and updated annually. The first to be acquired is the Tropical Rainfall Measuring Mission (TRMM) Tropical Cyclone Precipitation Feature (TCPF) Database - Level 1, which was created by researchers at Florida International University and the University of Utah (UU) from the UU TRMM Precipitation Feature database (*ghrc.nsstc.nasa.gov/hydro/details.pl?ds=trmmtcpfl1*). The TCPF database provides tropical cyclone data in a common framework for hurricane science research, aggregating observations from each of the TRMM instruments for each satellite orbit that was coincident with a tropical cyclone in any of the six cyclone-prone ocean basins. The image on the right shows a sample image from TCPF.



TCPF data depicting total rain accumulation in mm from Hurricane Katrina (August 23 - 30, 2005).

In addition, GHRC's Data and Information System is being redesigned to support analysis of hazardous weather events. This transition requires evolution of both the foundational data stewardship services and value-added knowledge augmentation services to enable easy discovery, access, and analysis of data centered on events. These services will include curation and aggregation of distributed resources including data, tools, and documents, as well as tools to enable exploratory data analysis via visualization for case study analysis.

Users may access the GHRC DAAC at *ghrc.nsstc.nasa.gov*. For additional information, contact the GHRC User Services Office at 256-961-7932 or *support-ghrc@earthdata.nasa.gov*.

[1]The name GHRC will be maintained for the time being, however, it will likely be changed to a name more reflective of its expanded mission.

ECOSTRESS Science Team Meeting

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Rick Allen and **Eric Wood** each discussed student projects, including the use of ET model Mapping EvapoTranspiration at high Resolution and Internalized Calibration (METRIC). METRIC differs from the previous two algorithms in that it uses an "in-scene" approach for calculating ET.

The Level 3 ET products can be used to assess the water cycle budget and serve as one of the inputs into calculating the Evaporative Stress Index (ESI) and Water Use Efficiency (WUE), which are planned ECOSTRESS Level 4 products. These ET-based indices help assess drought conditions as well as how efficiently plants are utilizing water and increasing in biomass, respectively.

Ben Bornstein presented an overview of the science data system (SDS), which collects the data (i.e., brings data from the spacecraft to the ground), and then processes, manages, and archives them. The ensuing discussion focused on a variety of topics including downlinking data from specific geographical areas and processes for data access (including making data available to external co-investigators prior to the delivery of the data to the LP DAAC). Users will identify specific areas for study that the SDS may be able to subset for ease of download.

Christine Lee discussed some of the expected science applications for ECOSTRESS data and gave an update on plans for the ECOSTRESS Early Adopters Program[3], which would include joint activities with applications users in agriculture and water resources.

[3] The SMAP mission was the first to implement an Early Adopter program, with several other missions, such as ICESat-2 and SWOT, working to develop Early Adopter programs and communities as well. For more information about the SMAP Early Adopters program, please see "The SMAP Early Adopters Program and the Impact on Prelaunch Research" in the January–February 2015 issue of *The Earth Observer* [**Volume 27**, **Issue 1**, pp. 24-28] and "Early Adopters Prepare the Way to Use ICESat-2 Data" in the July–August 2015 issue of *The Earth Observer* [**Volume 27**, **Issue 4**, pp. 31-35], or visit *smap.jpl.nasa.gov/science/early-adopters*.

The meeting also included an extended discussion of data products being developed to simulate expected ECOSTRESS retrievals. Simulated ECOSTRESS data can be used to assess the diurnal variability of ET being calculated by the three retrieval algorithms: PT-JPL, ALEXI, and METRIC. These datasets will also likely be used to support Early Adopter Program activities. This activity is being given high priority to help the Science Team prepare for receipt of actual ECOSTRESS data.

Conclusion

Once mounted onoard ISS, ECOSTRESS will be well-positioned to observe diurnal variability in terrestrial evapotranspiration and vegetation water stress. Being able to view Earth from the unique vantage point of ISS will enable critical science questions to be addressed, including the nature of the interactions between the water–energy–carbon cycle and the subsequent impacts on the terrestrial ecosystem. With a spatial resolution of approximately 60 m, ECOSTRESS has an opportunity to provide significant value to the applied sciences community. The most direct applications for the data will be in the areas of agriculture, water resource characterization and management, and drought monitoring. The data could potentially be applied more broadly for use in other areas: e.g., public health, weather forecasting, and wildfires assessment. ■

Tropical Fires Fuel Elevated Ozone Levels Over Western Pacific Ocean

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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.

A diverse team of atmospheric chemists, meteorologists, and modelers, including scientists from NASA, has traced the origins of mysterious pockets of high ozone concentrations and low water vapor in the air above the western Pacific Ocean near Guam to fires burning in Southeast Asia and in Africa—half a world away.

These pockets of *ozone*—a powerful greenhouse gas—are three times more concentrated than surrounding air and are found at around 30,000 ft (~9 km) in the lower part of Earth's atmosphere known as the troposphere, within the cruising altitude of most commercial airliners. As a greenhouse gas, ozone in the *troposphere* is an important contributor to global warming, but because it varies widely in where it occurs and how long it stays aloft, its true impact on climate change is hard to determine.

Scientists have observed the anomaly in ozone concentrations in the past, theorizing that the ozone had descended from a higher layer of the atmosphere called the *stratosphere*, where the air is dry and ozone acts as a protective layer, since it blocks harmful ultraviolet radiation from reaching Earth's surface.

But researchers studying the air over Guam during the winter of 2014 during a pair of field campaigns, called the Convective Transport of Active Species in the Tropics and the Co-ordinated Airborne Studies in the Tropics, found something surprising. The scientific instruments aboard the two research aircraft captured a more comprehensive picture of the chemicals traveling with the ozone pockets—chemicals such as hydrogen cyanide and acetonitrile, which originate in fires.

"When we saw high ozone [concentrations] we also saw very high concentrations of those other [chemical] species, so it was a pretty strong indicator that fires were at least playing some sort of role in the ozone production," said lead study author **Daniel Anderson** [University of Maryland, College Park] who was part of the international research team studying the atmosphere above the Western Pacific. The effort was funded by the National Science Foundation, the National Oceanic and Atmospheric Administration, and NASA. The results were published in the journal *Nature Communications* in January.

To determine if the ozone and the accompanying chemicals came from fires, Anderson and his colleagues used a computer model to trace the air pockets backwards through time based on wind and other factors—see **Figure**. The model uses observed weather data combined with the simulated behavior of the atmosphere to find where the wind

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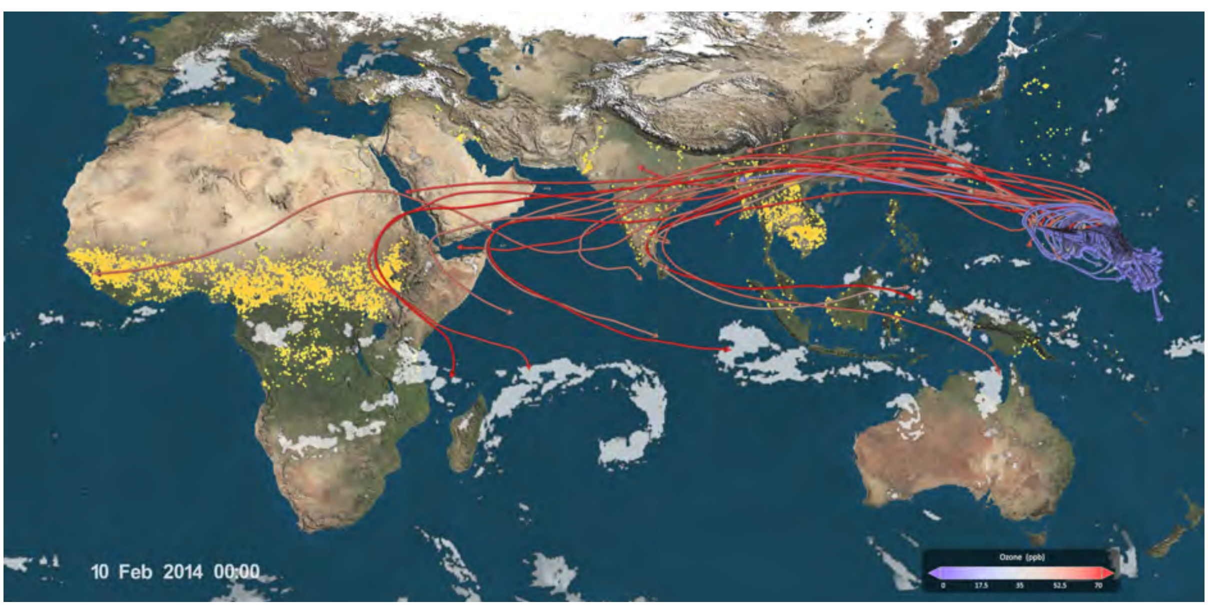

Figure. NASA-funded scientists have traced the origins of mysterious pockets of high ozone concentrations and low water vapor in the air above the western Pacific Ocean near Guam to fires (yellow dots) burning in Southeast Asia and tropical Africa 10-15 days earlier. They used a model to track the ozone back in time to find its source half a world away. The trajectories are coloured by observed aircraft ozone level where purple values represent low concentrations of ozone and red values represent high concentrations. **Image credit**: NASA's Science Visualization Studio

NASA Contributes to Global Standard for Navigation, Studies of Earth

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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 surface of the Earth is constantly being reshaped by earthquakes, volcanic eruptions, landslides, floods, changes in sea levels and ice sheets, and other processes. Since some of these changes amount to only millimeters (fractions of an inch) per year, scientists must make very precise measurements of the landscape and ocean in space and time in order to study their evolution and help mitigate their impacts.

The foundation for these precision measurements is the *terrestrial reference frame*, which serves the same purpose as landmarks along a trail. Earth-orbiting satellites and ground-based instruments make use of this reference system to pinpoint their own locations and, in turn, those of the features they are tracking. It is also the hidden framework relied upon by aircraft to determine their locations and by mobile phone apps that provide maps and driving directions. And it is a fundamental reference for interplanetary navigation of spacecraft.

NASA helps maintain the worldwide standard called the International Terrestrial Reference Frame (ITRF) and recently contributed to an update issued by the International Earth Rotation and Reference Systems Service's International Terrestrial Reference System Product Center at the Institut National de l'Information Géographique et Forestière (IGN), in Paris, France.

"The new release lays the groundwork for more detailed studies than ever before of global changes in Earth's ocean, ice sheets, land, and atmosphere," said **Stephen Merkowitz** [NASA's Goddard Space Flight Center (GSFC)—*Manager of Space Geodesy Project*].

Earth-observing satellites—such as the Jason-3 spacecraft, launched in January 2016 through a U.S.–European partnership, and the upcoming second Ice, Clouds, and Land-Elevation Satellite (ICESat-2) mission—will be among the beneficiaries of the new standard.

Officially called *ITRF2014*, the update released in late January is the ninth ITRF issued since 1992. More than a thousand observing stations run by NASA and other scientific institutions worldwide contributed to it, collecting data through 2014—see **Figure**.

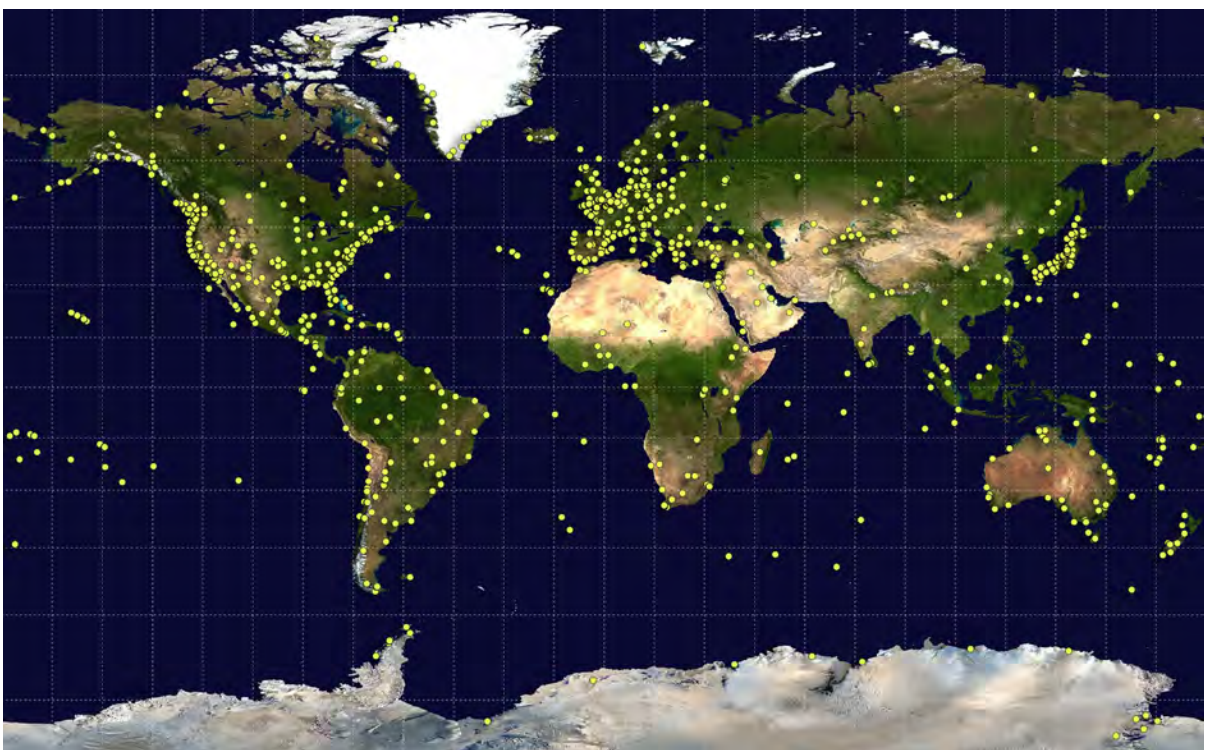

Figure. Sites around the world (yellow dots) contributed data and serve as "landmarks along a trail" for the newest update to a global standard called the International Terrestrial Reference Frame. Each site conducts precision measurements using at least one and up to four of the geodetic techniques described in this article. **Image credit:** GSFC/Earth Observatory

Global in nearly every sense of the word, the ITRF is made up of specific geographic positions around the world, along with information about how each one drifts over time. This is important because the positions move relative to each other, with some drifting more rapidly than others. The reference frame includes details about how quickly and in which directions the positions are expected to move.

Some of the drift happens because of the motion of Earth's tectonic plates, which is well understood. Drift motions may also include the gradual rebounding of land that was covered by ice sheets during the last ice age, as well as land subsiding due to climatic effects or human activity, e.g., withdrawal of groundwater. Less predictable are changes due to earthquakes. Large quakes will cause a sudden shift in position and also may alter the drift rate or direction at that location. Recent versions of the reference frame have started to include these effects.

"An important feature of the latest ITRF is that the model has a more sophisticated way of incorporating the effects of earthquakes," said **Chopo Ma** [GSFC—*Geophysicist*] who was involved in producing and analyzing data for the latest reference frame.

Helping to improve the ITRF is one of the primary goals of NASA's Space Geodesy Project. Four measurement techniques are used by stations worldwide to collect data for the reference frame.

In Satellite Laser Ranging (SLR) precise measurements are made by sending short laser pulses from ground stations to Earth-orbiting satellites equipped with suitable reflectors. The distance is calculated from the time it takes for the pulse to complete the round trip back to the ground station.

The second method is called Very Long Baseline Interferometry (VLBI). Ground stations spread across the globe observe dozens of quasars, which are distant enough to serve as stable reference points. By carefully timing when the signals from the quasars are recorded by each station, the precise geometry of the antenna network can be deduced, and Earth's orientation in space and its rotation rate can be measured.

The technique known as Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), takes advantage of the *Doppler effect*, which is what we hear when an ambulance's siren changes pitch as it drives toward or away from us. The frequency of a radio signal from a DORIS beacon experiences the same effect while traveling from Earth to an orbiting satellite. By measuring the frequency change, it's possible to work backward to figure out the distance from the beacon to the satellite.

The final method makes use of the *Global Navigation Satellite System (GNSS)*—a network that includes GPS and other navigation satellites. Radio signals are broadcast by GNSS satellites and received at many locations worldwide.

"The big advantage of GNSS is the dense network of stations distributed around the world," said **Richard Gross** [NASA/Jet Propulsion Laboratory (JPL)—*Manager of Terrestrial Reference Frame Combination Center*]. "For the reference frame, on the order of a thousand GNSS stations contribute position measurements."

Because there are GNSS receivers at the stations that perform the other three measurement techniques, GNSS also provides a method for tying together all four approaches. And when scientists worldwide want to measure how the ground is moving, they access the reference frame by using GNSS to determine their positions.

In preparation for the new reference frame, research teams worldwide carried out data analysis, looking at between 20 and 30 years of data for each method. Scientists at GSFC and the University of Maryland, Baltimore County, coordinated the data analysis for VLBI, SLR, and DORIS, and JPL contributed GNSS data. All of the geodetic data for the reference frame have been archived at the NASA Crustal Dynamics Data Information System, located at GSFC, and distributed to users worldwide.

Looking forward, NASA is upgrading the stations in its Space Geodetic Network. The Space Geodesy Project at GSFC is managing these upgrades, and work is already under way at stations in Hawaii and Texas. The upgraded stations will help fill in geographic gaps in the global system, helping to improve future versions of the reference frame.

In addition, scientists are looking at other possible approaches for combining the four data types to produce an improved reference frame. Research on advancing the ITRF is conducted not only at IGN, but also at JPL's Terrestrial Reference Frame Combination Center and at a similar center at the Deutsches Geodätisches Forschungsinstitut in Munich, Germany. Each center produces its own independent solution, which scientists will compare to see what they can learn from different approaches.

"We renew the International Terrestrial Reference Frame every few years because it's more than a set of geographical positions," said **Frank Lemoine** [GSFC], who is involved in producing and analyzing data for the new standard. "It's a projection about what will happen to those positions in the future, and our ability to extend the reference frame into the future gets better and better over time."

For more information about NASA's Space Geodesy Project, visit *space-geodesy.nasa.gov*. ■

NASA Demonstrates Airborne Water Quality Sensor

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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.

Monitoring the quality of freshwater supplies is a global concern, especially in thirsty California, where the San Francisco Bay-Delta Estuary and its watershed serve as a major freshwater source. Now scientists at NASA/Jet Propulsion Laboratory (JPL) and the U.S. Geological Survey (USGS) in Menlo Park and Sacramento, California, have successfully demonstrated how a NASA-developed airborne environmental monitoring instrument can be applied to help water managers monitor water quality not only in San Francisco Bay, but potentially in other inland and coastal water bodies around the world.

In a study published in the journal *Environmental Science & Technology*, researchers combined water sample measurements collected by USGS scientists aboard a high-speed boat in northeastern San Francisco Bay with data collected by JPL scientists at the same time onboard a specially instrumented Twin Otter aircraft flying overhead. The plane carried the JPL-developed Portable Remote Imaging Spectrometer (PRISM), which measures the amount and wavelength of visible light and near-infrared radiation reflected toward the instrument from the water below. The PRISM data allow researchers to detect the unique spectral signatures of several water constituents typically used as indicators of water quality—see **Figure**. When the two datasets were later analyzed and compared in laboratories, the PRISM data closely matched the water quality information collected from the boat.

The benefit of PRISM is that it can greatly expand the spatial coverage of traditional boat- and fixed-monitoring, station-based approaches used for water quality monitoring. For example, a single PRISM airborne flight can assess the water quality of much of the San Francisco Bay-Delta Estuary; similar coverage using a boat would take weeks.

For this study, the researchers analyzed *turbidity* (how cloudy the water is), *chlorophyll-a* (an indicator of phytoplankton in the water), *dissolved organic carbon* (a source of undesired disinfection by-products produced during the treatment of drinking water), and sediments suspended in the water. Dissolved organic carbon is also a useful indicator of the amount of dissolved *methylmercury*, a potent neurotoxin that tends to accumulate in fish and other wildlife in the San Francisco Bay-Delta Estuary. The experiment demonstrated how a single image from PRISM can instantaneously provide a detailed snapshot of these important water quality indicators over a large and diverse water body.

New imaging spectrometers like PRISM can enable accurate detection of water quality indicators that were previously difficult to measure using existing satellite sensors. Scientists hope to apply the PRISM technology to sensors on future Earth-orbiting satellites that can provide continuous global monitoring.

"This study successfully demonstrated the potential of remote sensing to monitor water quality indicators and their variability in the San Francisco Bay-Delta Estuary—one of California's most important water resources—where wetland restoration, human activities, and climate change can impact water quality and

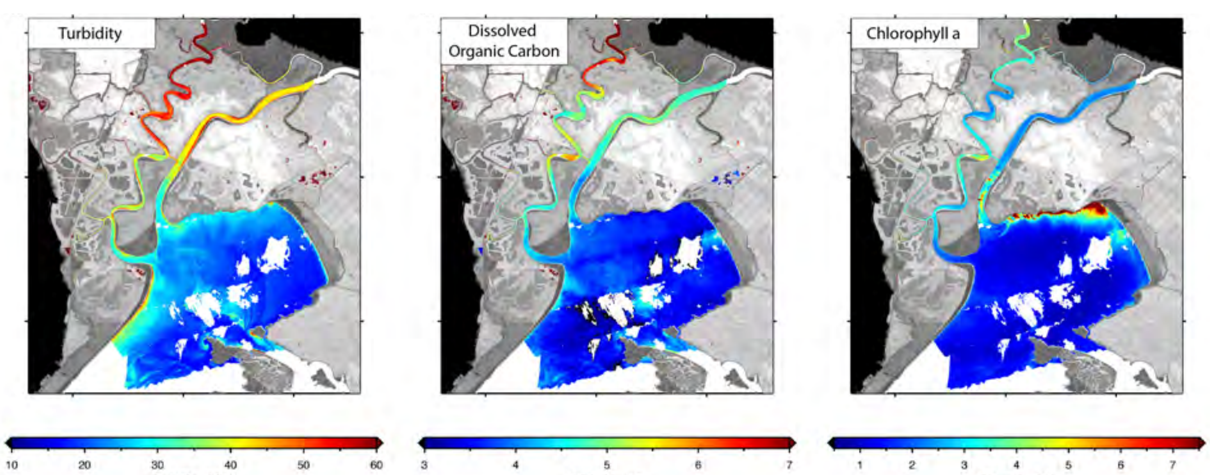

Figure. [*Left to right*] These maps, derived using data from the Portable Remote Imaging Spectrometer (PRISM), show turbidity (i.e., water clarity), dissolved organic carbon, and chlorophyll-a in the San Francisco Bay-Delta Estuary's Grizzly Bay and Suisun Marsh in April 2014. **Image credit**: NASA/JPL-California Institute of Technology ecosystem productivity," said study lead author **Cédric G. Fichot** [JPL—*Postdoctoral Researcher*]. "Remote sensing holds great promise for efficiently collecting water quality information over large areas, at high spatial resolution, and with good accuracy." Fichot led the study through a collaboration between NASA, USGS, and the Delta Science Fellows Program.

Humans have profoundly altered the ecosystems of the San Francisco Bay-Delta Estuary and its watershed over the past 150 years. Water quality monitoring is critical to managing this important water resource and assessing its ecosystem health. USGS has been consistently monitoring water quality in San Francisco Bay for almost 50 years. But vessel-based water quality monitoring programs are time-consuming and labor intensive.

The researchers say the successful, accurate detection of water quality indicators by an airborne sensor is important because some of them are particularly difficult to measure in the laboratory due to sampling precision and/or technical costs.

"While turbidity has been mapped remotely for years with satellites, this time we were able to estimate the individual components of turbidity: suspended sediments, dissolved organic carbon, and chlorophyll-a," said co-author **Lisamarie Windham-Myers** [USGS—*Ecologist*].

"One of the most exciting things about this study was that it demonstrated our ability to take a mile-high view of methylmercury concentrations across a complex mosaic of wetlands and open water," said co-author **Mark Marvin-DiPasquale** [USGS—*Microbiologist*]. "This represents the first imaging for this toxic substance at this resolution and spatial scale."

"Considering the difficulty and elevated costs of measuring methylmercury using samples, this new remote sensing technique represents a major leap forward in our ability to detect hot spots of this contaminant in wetlands," added Fichot.

The concurrent boat/aircraft measurement approach was also able to successfully capture the rapid changes taking place within the estuary, where tides cause water quality to change over timescales of minutes and spatial scales of feet, said co-author **Brian Bergamaschi** [USGS—*Biogeochemist*]. "This approach of using a high-speed boat to map conditions in the water across a broad area as the sensor is flown overhead worked well as a way to relate the laboratory measurements directly to airborne sensor data," he said. Bergamaschi added that the team is now using the technique to calibrate satellite observations to help broaden the view. ■

Tropical Fires Fuel Elevated Ozone Levels Over Western Pacific Ocean

continued from page 31

came from one hour previously, and then based on the new location, where the wind came from the hour before that, and so on, determining the history of the air pocket as it moved through the atmosphere.

Anderson and his colleagues traced the ozone-laden air pockets back 10 to 15 days in most cases—right back to fires in either Southeast Asia, about 2000 mi (3219 km) away, or tropical Africa, over 8000 mi (~12,875 km) away.

"We were surprised at how well it worked out, because it created a very clear picture," Anderson said.

Ozone is a byproduct of burning organic material like trees and other vegetation—or of the combustion of fossil fuels in industrial settings. Burning organic matter transforms part of the carbon that was in the vegetation into its gaseous forms, including carbon dioxide, methane, and *volatile organic compounds*—carbon-based compounds that change easily from liquid to vapor, and when combined with oxides of nitrogen, in the presence of sunlight, result in the production of tropospheric ozone.

The smoke plumes from the fires and updrafts from large storm systems then lift the ozone—along with ozone precursors, which continue to react in transit, and other tracer compounds produced by fires—high into the atmosphere where winds transport them thousands of miles away.

The high-altitude transport also explains why the air pockets are drier than the surrounding air, Anderson said. Dry air is normally associated with the stratosphere—the previous hypothesis—because air found higher in the atmosphere is colder, and thus cannot hold as much moisture. But the upper troposphere is also much colder than the lower troposphere, achieving the same effect of drying out the high ozone air pockets. Then, when they slowly descend over the western Pacific due to normal atmospheric circulation, the air pockets continue to have lower water vapor than their surroundings.

Tropical fires have long been known to have an impact on the atmosphere, said **Bryan Duncan** [NASA's Goddard Space Flight Center—*Research Scientist*], who was not involved in the research. The next step, he said, will be to evaluate how this new understanding of tropical fires as another source for ozone in the western Pacific affects the greenhouse potential for both the region and the climate on a broader scale. "What they've shown here is that it's more complicated than we thought," he said. ■

NASA Earth Science in the News

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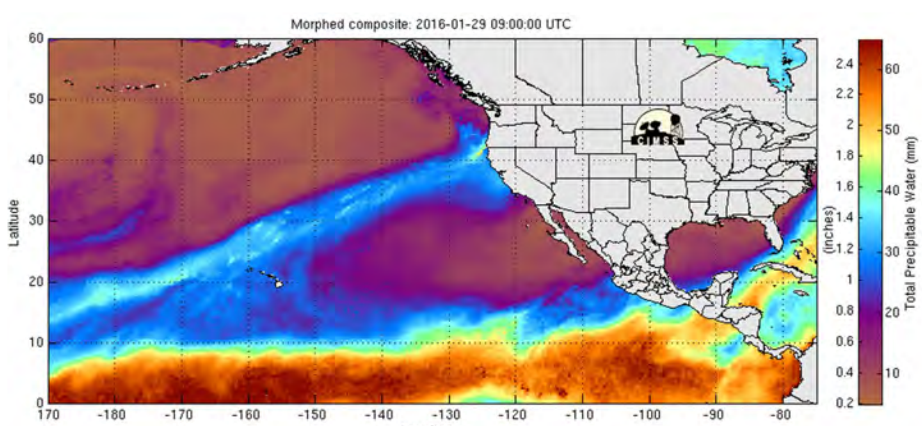
The Middle East Just Suffered Its Worst Drought in 900 Years, March 4, *The Washington Post*. A NASA study has found that a drought that affected the Middle East over the past decade is perhaps the worst the region has experienced in nearly a millennium. The scientists, who published their study in the *Journal of Geophysical Research-Atmospheres*, examined the tree-ring record of the Eastern Mediterranean—countries that include Cyprus, Israel, Jordan, Lebanon, Turkey, and Syria—to determine when water was most scarce. A thinner ring signifies drier years, whereas thicker ones indicate when water was in greater abundance. "The magnitude and significance of human climate change requires us to really understand the full range of natural climate variability," said lead author of the study **Ben Cook** [NASA's Goddard Institute for Space Studies (GISS)—*Climate Scientist*], emphasizing the need to take a larger look at the forces at play.

Atmospheric River Storms Can Reduce Sierra Snow, March 3, *phys.org*. A new study by NASA and several partners has found that in California's Sierra Nevada, *atmospheric river* storms (see image, below) are two-and-a-half times more likely than other types of winter storms to result in destructive *rain-on-snow* events, where rain falls on existing snowpack, causing it to melt. Those events increase flood risks in winter and reduce water availability the following summer. The study, based on NASA satellite- and ground-based data from 1998 through 2014, is the first to establish a climatological connection between atmospheric river storms and rain-on-snow events. Partnering with NASA on the study were University of California, Los Angeles; Scripps Institution of Oceanography, San Diego; and NOAA's Earth System Research Laboratory in Boulder, CO.

Greenland's Ice Is Getting Darker, Increasing Risk of Melting, March 3, *phys.org*. A new study of satellite data reveals that Greenland's snowy surface has been getting darker over the past two decades, absorbing more heat from the sun, thereby increasing snow melt. The results suggest that this trend is likely to continue, with the surface's reflectivity, or *albedo*, likely to decrease by as much as 10% by the end of the century, the study says. While the study indicates that soot blowing in from wildfires contributes to the problem, it apparently hasn't been driving the change. The real culprits are two feedback loops created by the melting itself. The results, published in the European Geophysical Union journal, *The Cryosphere*, have global implications. Fresh meltwater pouring into the ocean from Greenland raises sea level and could affect ocean ecology and circulation. "You don't necessarily have to have a 'dirtier' snowpack to make it dark," said lead author **Marco Tedesco** [GISS—*Adjunct Scientist*]. "A snowpack that might look 'clean' to our eyes can be more effective in absorbing solar radiation than a dirty one. Overall, what matters is the total amount of solar energy that the surface absorbs. This is the real driver of melting."

NASA's IMERG Measures Flooding Rainfall in Peru, March 3, *phys.org*. Heavy rainfall recently caused flooding, landslides, and power outages in some areas of Peru. NASA's Integrated Multi-satellitE Retrievals for Global Precipitation Measurement (GPM) [IMERG] measured that rainfall by using a merged precipitation product from a constellation of satellites—including data from the GPM Core Observatory, a satellite co-managed by NASA and the Japan Aerospace Exploration Agency. The GPM Core Observatory provides next-generation observations of rain and snow



This image depicts an atmospheric river storm that occurred between January 28-30, 2016, bringing half an inch to an inch of rain to many locations in central and southern California. **Image credit:** University of Wisconsin/Cooperative Institute for Meteorological Satellite Studies worldwide every three hours. Extremely heavy rainfall was reported in northern Peru on February 26 and February 27, 2016. Thousands were made homeless and at least two people were reportedly killed as a result of the severe weather. This year's strong El Niño was partially blamed for the abnormally high rainfall in that area. NASA's IMERG data, collected from February 23-29, 2016, were used to estimate rainfall totals over this area of South America. The highest rainfall total estimates for this period were over 700 mm (27.6 in). These extreme rainfall total estimates were shown east of the Andes in southeastern Peru and Bolivia.

Clean Energy May Help Save Billions In Health Costs, February 25, *Tech Time*. Hundreds of thousands of lives could be saved if the U.S. would cut carbon emissions adequate enough to prevent a 2 °C (3.8 °F) increase in global temperatures. In light of this, such a move may help save billions in health costs. In the Paris agreement concluded in December 2015, hundreds of countries across the globe promised to reduce emissions to curb global warming. With the U.S. as one of the leading developed countries, it is likely to lead the move to reduce carbon emissions by about 80% in 50 years. In a paper published in the journal *Nature Climate Change*, researchers at Duke University and NASA's GISS said that cutting carbon emissions could save up to 295,000 lives by 2030 and could save about $250 billion in health benefits.

NASA Plans to Launch CubeSats for Improved Understanding of Earth, February 23, *aerospace-technology.com*. The Earth Science Technology Office (ESTO), part of NASA's Earth Science Division, has selected four new projects to be developed, built, and launched into low-Earth orbit to test new technologies before launching future Earth observation missions. The new technologies could provide improved understanding of our planet. The development of the CubeSat Radiometer Radio Frequency Interference Technology Validation (CubeRRT) project will be led by Ohio State University. The CubeRRT project will be designed to observe, detect, and then use the mission's results to mitigate radio frequency interference (RFI) for microwave radiometers. The Compact Infrared Radiometer in Space (CIRiS) project will be led by Ball Aerospace & Technologies and will use an existing instrument to ensure it is CubeSat-compatible in order to validate instrument performance in low-Earth orbit in future missions. NASA/Jet Propulsion Laboratory (JPL) will lead the CubeSat Infrared Atmospheric Sounder (CIRAS) project, which seeks to develop a CubeSat-size instrument that can measure temperature and water vapor profile levels in the lower troposphere. The last project selected is Precipitation Profiling Radar in a CubeSat (RainCube), which will be the first active radar on a CubeSat platform; it too will be led by JPL.

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****.* ■

Undefined Acronyms Used in the Editorial and Article Titles

CALIPSO	Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations
CNES	Centre National d'Etudes Spatiales [French Space Agency]
EO-1	Earth Observing–1
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
GFZ	GeoForschungsZentrum [German Research Center for Geosciences]
GPM	Global Precipitation Measurement
GRACE	Gravity Recovery and Climate Experiment
GSFC	NASA's Goddard Space Flight Center
JPL	NASA/Jet Propulsion Laboratory
LaRC	NASA's Langley Research Center
MIT	Massachusetts Institute of Technolgy
MODIS	Moderate Resolution Imaging Spectroradiometer
NOAA	National Oceanographic and Atmospheric Administration
SORCE	Solar Radiation and Climate Experiment
UT/CSR	University of Texas Center for Space Research

NASA Science Mission Directorate – Science Education and Public Outreach Update

Free Education Webinar Series from the GOES-R Education Proving Ground

The Geostationary Operational Environmental Satellites (GOES)-R Series is the next generation of the National Oceanic and Atmospheric Administration's (NOAA) geostationary Earth-observing systems, the first satellite of which is scheduled to be launched by NASA in October 2016. To help educators prepare for the new satellite imagery and data that will be available during the GOES-R era, the GOES-R Education Proving Ground is hosting a series of education webcasts leading up to launch.

The webinars will take place on the following Saturday mornings at 11:30 AM Eastern Time: **April 23, 2016**: GOES-R Resources and Educational Tools; and **September 17, 2016**: Countdown to Launch!

For more information, including log-in instructions for the webinars, visit *cimss.ssec.wisc.edu/education/goesr*.

STEM on Station—Welcome Home, Scott Kelly!

Astronaut **Scott Kelly** spent a *#YearinSpace* and has returned to Earth. Learn about the science behind Kelly's mission and find out about the top "Ten Things to Know" about his time in space at *www.nasa.gov/mission_pages/station/research/news/top_ten_1YM*.

Learn more about ways you can bring the space station into your classroom by visiting NASA's science, technology, engineering, and mathematics (STEM) on Station website at *www.nasa.gov/education/STEMstation*. While you are there, stop by and learn more about the year-long mission and how it is helping us on our *#JourneytoMars*.

Host a Real-Time Conversation with Crew Members aboard the International Space Station

Proposal Deadline: April 15, 2016

The U.S. Amateur Radio on the International Space Station (ARISS–US) is now accepting proposals from U.S. schools, museums, science centers, and community youth organizations to host amateur radio contact events between January 1 and June 30, 2017.

Using amateur radio during this once-in-a-lifetime opportunity, students can ask astronauts on the ISS questions about life in space and other space-related topics for the approximately 10 minutes the ISS will be in range for contact, using ground stations the students help assemble.

For proposal information, visit *www.arrl.org/hosting-an-ariss-contact*.

Call for Submissions—NASA Announcement for High Impact/Broad Implementation STEM Education Partnerships

Submission deadline: December 31, 2016

The NASA Headquarters Office of Education, in cooperation with several other agency offices, announces a competition to improve STEM education.

NASA Education seeks to partner with eligible domestic or international organizations to reach wide and diverse audiences, with priority on collaboration in several STEM and related areas.

For more information about this opportunity, visit NSPIRES at *go.nasa.gov/1RZwWCi*.

New NASA Women of STEM Website

Celebrate Women's History Month with the new NASA Women of STEM website! Through their accomplishments and dedication to their jobs, women at NASA embody the essence of Women's History Month. Read career profiles, watch videos and more! Visit the new website at *www.nasa.gov/education/womenstem*. ■

EOS Science Calendar

April 18–19, 2016
LCLUC Science Team Meeting, Bethesda, MD.
lcluc.umd.edu/meetings.php

April 26–28, 2016
CERES Science Team Meeting, Hampton, VA.
ceres.larc.nasa.gov

May 10–12, 2016
CLARREO Science Definition Team Meeting
Ann Arbor, MI.

June 6–10, 2016
MODIS/VIIRS Science Team Meeting, Silver Spring, MD.
modis.gsfc.nasa.gov/sci_team/meetings

June 7–10, 2016
ASTER Science Team Meeting, Tokyo Japan.

August 30–September 1, 2016
Aura Science Team Meeting Rotterdam,
The Netherlands.
aura.gsfc.nasa.gov

October 5–7, 2016
GRACE Science Team Meeting, Potsdam, Germany.
www.csr.utexas.edu/grace/GSTM

October 31–November 4, 2016
Ocean Surface Topography Science Team Meeting
La Rochelle, France.

Global Change Calendar

April 17–22, 2016
European Geosciences Union General Assembly,
Vienna, Austria.
www.egu2016.eu

April 20–21, 2016
MuSLI Science Team Meeting, Bethesda, MD.
lcluc.umd.edu/meetings.php

May 6–7, 2016
Second EARSeL SIG LU/LC and NASA LCLUC Joint Workshop, Prague, Czech Republic.
lcluc.umd.edu/Documents/Announcements/Leaflet_workshop.pdf

May 22–26, 2016
Japan Geoscience Union Meeting, Makuhari Messe, Japan.
www.jpgu.org/meeting_e2016/greeting.html

July 31–August 5, 2016
AOGS 13th Annual Meeting, Beijing, China.
www.asiaoceania.org/aogs2016/public.asp?page=home.htm

October 25–28, 2016
GSA Annual Meeting, Denver, CO.
www.geosociety.org/meetings/2016

April 18–21, 2017
A-Train Symposium, Pasadena, CA.

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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 15th of the month preceding the publication—e.g., December 15 for the January–February issue; February 15 for March–April, and so on.

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