Over Thirty Years Reporting on NASA's Earth Science Program

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The Editor's Corner

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In a year marred by the pandemic (nine months and counting of telework for most NASA employees as of this writing) and other converging crises, it is a welcome respite to close out our final issue of the year reporting on the flawless launch of the joint U.S.–European[1] Sentinel-6 Michael Freilich mission on November 21, 2020, from Vandenberg Air Force Base aboard a SpaceX Falcon 9 rocket—see photo on page 4.

Soon after unfolding and activating its solar arrays, ground controllers successfully acquired the satellite's signal. Initial telemetry reports indicate that the spacecraft is in good health. Sentinel-6 Michael Freilich will continue undergoing a series of exhaustive checks and calibrations before it starts collecting science data in a few months. The mission's first measurements of sea level anomalies (preliminary), released on December 10, are shown in the image below. The first data are expected to be publicly available in about a year.

For nearly 30 years, NASA and its partners have maintained a continuous time series of precise measurements of sea level height. It began with TOPEX/Poseidon (launched in 1992), has continued with the Jason series of satellites—Jason-1 (2001), OSTM/Jason-2 (2008), and Jason-3 (2016)—and now the baton passes to Jason-Continuity of Service, which comprises both Sentinel-6 Michael Freilich and its twin "sister" Sentinel-6B (planned for a 2025 launch). Together, these two missions should extend the sea level time series for at least another decade.

Sentinel-6 Michael Freilich honors the life and legacy of Michael Freilich, the former director of NASA's Earth Science Division who passed away on August 5, 2020. Freilich was a tireless advocate for advancing Earth observations from space. His family and close friends were able to attend the launch. While it is unfortunate "Mike" did not live to see the spacecraft that bears his name reach orbit, without a doubt he would be proud of this accomplishment. Congratulations to the entire Sentinel-6 Michael Freilich team on the launch and initial data, and best wishes for a successful mission.[2]

[1] Sentinel-6 mission partners include NASA, NOAA, EUMETSAT, CNES, and the European Commission.
[2] More information about Sentinel-6 Michael Freilich, including several quotes from NASA Headquarters officials and others, can be found at *www.nasa.gov/press-release/nasa-us-and-european-partners-launch-mission-to-monitor-global-ocean*.

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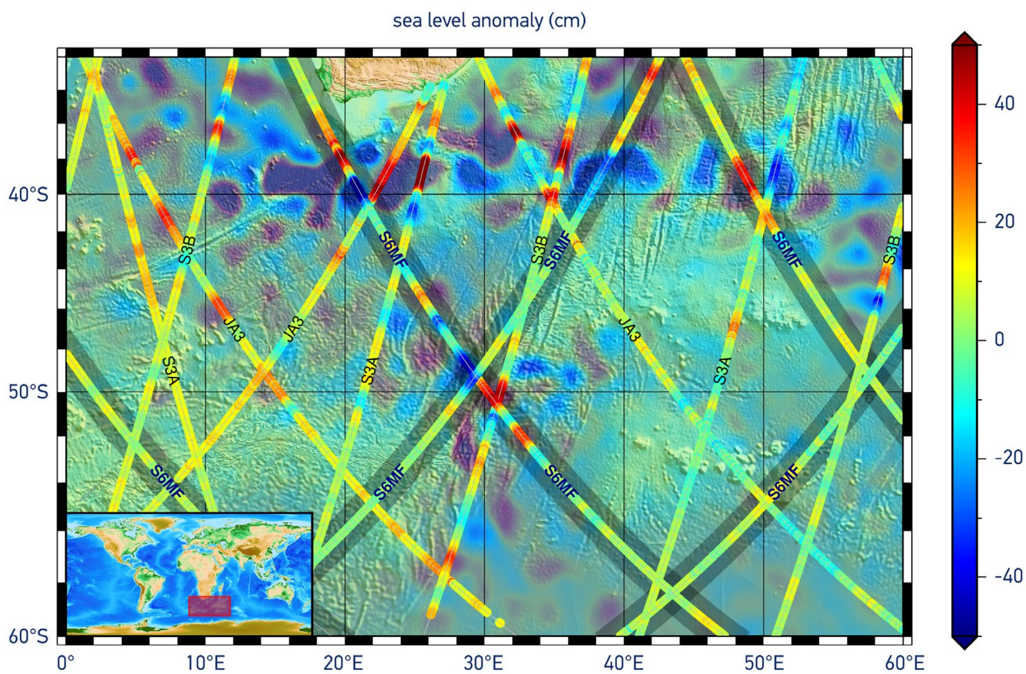


Figure. The data in this graphic are the first sea surface height anomaly measurements from the Sentinel-6 Michael Freilich satellite, which launched November 21, 2020. They show the ocean off the southern tip of Africa, with red shades indicating higher sea level relative to blue shades, which indicate lower sea level. **Credit:** EUMETSAT

In This Issue

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

Our feature article in this issue focuses on how researchers and technologists worldwide are turning their attention to *CubeSats* and other "small satellites" as a means of getting the most bang for the research buck. A subclass of nanosatellites with remarkable capabilities given their small size (a standardized 10 cm cube unit), NASA and other space agencies are increasingly supporting observations from CubeSats, which are a subclass of nanosatellites with remarkable capabilities given their small size (a standardized 10 cm cube unit) and are flown largely as piggy-back payloads of opportunity. CubeSats are already making contributions to terrestrial remote sensing—and to space science as well—having platforms that include the basic functional satellite modules (power; command, control, and communications; thermal stability; station-keeping) as well as sensors that provide data comparable to and/or supportive of measurements from larger platforms. The thriving community of CubeSat practitioners makes this a viable modality to explore for suitable research and applications. Turn to page 5 of this issue to learn more about how CubeSats are being used for Earth science investigations.

While many of us have had to learn to work exclusively remotely over the past nine months, Earth observing satellites continue to infer the state of the planet from a distance without interruption during the pandemic. For example, now more than two years after launch, the ICESat-2 spacecraft remains healthy; its ATLAS instrument is performing nominally and continues to collect high quality science data—15,000 hours' worth, as of December 3, 2020. An ICESat-2 virtual Science Team Meeting took place September 21-22, 2020. NASA Headquarters had announced a new ICESat-2 Science Team (ST) in February 2020, and this was the first time that the newly selected ST met (albeit virtually). Turn to page 27 of this issue to learn more about the status of ICESat-2.

Moving out into deep space to the L-1 Lagrange point, the NASA Earth observing instruments (EPIC and NISTAR) onboard DSCOVR are doing well. The mission returned to full operational status on March 2, 2020, after being in safe mode since June 27, 2019, as a result of deteriorating gyros. The spacecraft now relies solely on its star tracker for navigation. The NASA instruments continue to function well with advances in calibration of both EPIC and NISTAR, data processing, and science data acquisition. DSCOVR has sufficient fuel and power generation capabilities to operate at least through 2030—and probably longer. The recent Earth Science Senior Review (results described on page 3) agreed with this assessment and rendorsed continued funding for the next three years. The DSCOVR ST held a virtual meeting October 6-8, 2020; turn to page 39 of this issue to learn more about the current status of DSCOVR.

NASA's missions in development also continue to make progress despite the pandemic. As an example, the PACE mission represents NASA's next major advance in the combined study of Earth's ocean-atmosphere-land system. Although progress has been slowed by the pandemic, the mission has persevered with the launch now scheduled for late 2023.[3] A limited and phased number of PACE-related activities safely resumed at GSFC in July 2020. All of these focus on building and evaluating engineering test units and flight units for the spacecraft and the three-instrument payload. PACE's primary instrument—the hyperspectral scanning Ocean Color Instrument (OCI)—recently passed element-level Technical Readiness Reviews and has partially resumed engineering test unit evaluation.[4] The flight unit for the Spectropolarimeter for Planetary Exploration (SPEXone), a multi-angle polarimeter being built and overseen by the SRON Netherlands Institute for Space Research and Airbus Defence and Space Netherlands, is undergoing final ambient calibrations and pre-ship reviews. SPEXone will be delivered to GSFC in February 2021. Also, the Hyper-Angular Rainbow Polarimeter (HARP2), a second multi-angle polarimeter being built by the Earth and Space Institute at the University of Maryland, Baltimore County (UMBC), continues to undergo assembly and testing. HARP2 will be delivered to GSFC in the final quarter of 2021.

PACE continues to have active community engagement, despite the pandemic. Its Science and Applications Team, a competitively selected collection of projects from academia, industry, and government, continues to collaborate with the Project to advance the scientific capabilities of the mission. The PACE Applications Program organized and hosted a successful virtual PACE Applications Workshop on September 23-24, 2020. It was an opportunity to initiate an interdisciplinary dialogue focused on PACE and how its anticipated data products could support a variety of societal needs. It is anticipated that this will be the first in a series of annual PACE Applications events. Turn to page 18 of this issue to learn more about this meeting.

On the subject of future missions, on September 11 and 14, NASA's Terrestrial Hydrology Program (THP) met to discuss ongoing efforts to advance global snow water equivalent (SWE) and other snow parameter observations that are needed to better characterize the water cycle. In recognition of crucial knowledge gaps, the 2017 Earth Science Decadal Survey[5] identified snow measurements as an important priority. NASA's SnowEx campaigns (2016–17, 2020, and planned for 2021) are part of a multiyear, THP-sponsored effort to test and develop remote sensing technologies to monitor snow characteristics—SWE in particular—from space, and to identify optimum multisensor synergies and model assimilation for mapping critical snowpack properties in a future satellite mission. Turn to page 31 of this issue to learn more about the SnowEx virtual meeting.

Every three years, the NASA Headquarters Earth Science Division conducts a review of its post-prime extended missions to assess overall progress toward achieving mission objectives and viability for continued extension. The 2020 Earth Science Senior Review evaluated 13 NASA Earth Science satellite and instrument missions currently in extended operations: Aqua, Aura, CALIPSO, CloudSat, CYGNSS, DSCOVR Earth Science Instruments, ECOSTRESS, GPM Core Observatory, LIS on ISS, OCO-2, SAGE III on ISS, SMAP, and Terra. Based on proposals submitted by each mission's project scientist in early March 2020, the assessment consisted of a series of comprehensive reviews of current operating mission science, operational utility and national interest, and technical and cost performance. The Senior Review Panel, consisting of community scientists, was tasked with reviewing mission proposal submissions, as well as input from a separate National Interests Panel, for the fiscal years 2021-23 and 2024-26. The panel summarized the process and their review findings in a publicly available report (*science.nasa.gov/earth-science/missions/operating*) at the end of August. All missions were endorsed for extension for fiscal years 2021-2023 and notionally the following three fiscal years, with the exception of one mission due to technical reasons (see Table 2 of the report). Congratulations to all the mission teams for their hard work in preparing proposals and contributing to, as the reports states, a "transformative change in our scientific understanding of the Earth System." And a special thanks to all review panel members for their willingness to participate in this critical activity.

Finally, a longstanding tradition is for the NASA Science Mission Directorate to participate in the Fall Meeting of the American Geophysical Union (AGU)—and this year was no exception despite the pandemic. NASA and researchers from around the world met virtually from December 1–17, 2020. The virtual NASA Science exhibit featured a Science Theater, which included 75 presentations hosted on *YouTube*; live daily chat times; the 2021 NASA Science calendar (available in English and Spanish);[6] and specially

[3] To learn more, see "PACE: Persistence and Perseverance Despite Pandemic" at *svs.gsfc.nasa.gov/13658https://svs.gsfc.nasa.gov/13658*.

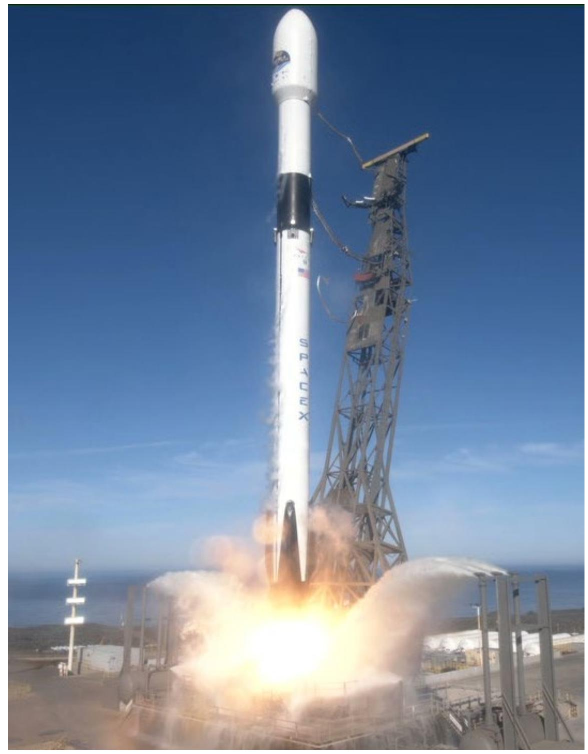
[4] To learn more, see "PACE OCI Instrument Under Construction" at *svs.gsfc.nasa.gov/13589*.

[5] The report is called *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space.* It can be downloaded from *doi.org/10.17226/24938*.

[6] Unlimited downloads of the 2021 NASA Science Calendar are available in English at *science.nasa.gov/2021calendar* and Spanish at *ciencia.nasa.gov/calendario2021*. The calendar is also available through the U.S. Government Publishing Office at *bookstore.gpo.gov/products/2021-explore-science*.

curated resources from across the Science Mission Directorate, including Earth Science, Planetary Science, Heliophysics, Astrophysics, Biological and Physical Sciences, and Science Activation. We will have detailed coverage of the NASA exhibit and other AGU happenings in our January–February 2021 issue.

As 2020 comes to an end, it is an understatement to say that the past nine months have been unparalleled in recent history. The impact was definitely felt at NASA, where in the span of just a few days in mid-March, on site work switched to telework. Informal communication that used to take place in hallways, lunchrooms, conference rooms, and offices had to similarly move to a virtual landscape. While it was an abrupt adjustment, compounded by the learning curve for multiple video conferencing software tools, I continue to be amazed at the adaptability shown by individuals and their organizations. I am grateful to be part of a resilient and committed Earth science community that has continued to be productive despite the serious problems and overall cacophony of 2020. I'm optimistic that 2021 will be a better year for all of us personally and societally. I wish everyone a happy holiday season and a healthy, safe, and prosperous New Year. ■



A SpaceX Falcon 9 rocket with the Sentinel-6 Michael Freilich satellite launched on November 21, 2020, from Space Launch Complex 4E at Vandenberg Air Force Base in California. **Photo credit:** NASA TV

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

ATLAS	Advanced Topographic Laser Altimetry System
AGU	American Geophysical Union
CALIPSO	Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations
CNES	Centre National d'Études Spatiales [French Space Agency]
CYGNSS	Cyclone Global Navigation Satellite System
DSCOVR	Deep Space Climate Observatory
ECOSTRESS	ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station
EPIC	Earth Polychromatic Imaging Camerat
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
GPM	Global Precipitation Measurement
GSFC	NASA's Goddard Space Flight Center
ICESat-2	Ice, Cloud, and land Elevation Satellite–2
ISS	International Space Station
LIS	Lightning Imaging Sensor
NOAA	National Oceanic and Atmospheric Administration
NISTAR	National Institute of Standards and Technology (NIST) Advanced Radiometer
OCO-2	Orbiting Carbon Observatory–2
OSTM	Ocean Surface Topography Mission
PACE	Plankton, Aerosol, Cloud, ocean Ecosystem
SAGE	Stratospheric Aerosol and Gas Experiment
SMAP	Soil Moisture Active Passive

CubeSats and Their Roles in NASA's Earth Science Investigations

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Introduction

It seems that—once again—what's old is new.

The first U.S. satellite was, by recent standards, a small one. Despite its limited size (see **Photo**), Explorer-1 had onboard an Earth-science sensor, the data from which resulted in the discovery and beginning characterization of the Van Allen Radiation Belts that surround our planet. It was truly a seminal moment in examining our home planet from the vantage point of space.

Photo. The three men responsible for the success of Explorer 1, America's first Earth satellite which was launched January 31, 1958, are shown holding aloft a model of the satellite. At left is **William H. Pickering**, former director of the Jet Propulsion Laboratory (JPL), which built and operated the satellite. **James A. Van Allen**, center, of the State University of Iowa, designed and built the instrument on Explorer that discovered the radiation belts that circle the Earth. At right is **Wernher von Braun**, leader of the Army's Redstone Arsenal team which built the first stage Redstone rocket that launched Explorer 1. **Photo and caption credit:** NASA

Over time and owing to seemingly never-ending advances of science and technology, Earth remote sensing satellites increased in size to the point where the original plans for "System Z," which quickly evolved into NASA's Earth Observing System (EOS), envisioned massive platforms studded with instrumentation. For a variety of reasons, these grand "Battlestar Galactica"[1] concepts were scaled back considerably long before EOS became reality. However, Terra—the first EOS "flagship" to launch—was still the size of a small bus.[2] The other two EOS flagship missions (Aqua and Aura) used a common spacecraft design that was similar to that of Terra, but slightly smaller in size than their "sister spacecraft."

That trend continues. While there is increasing discussion of extremely small sensors (sometimes referred to as "motes" or "dust"), their routine realization is still underway. But before things get to that level of miniaturization, there is already increasing interest in utility for smaller satellites (*SmallSats*) that are gaining significant roles in many scientific areas. SmallSats are spacecraft with a mass less than 1100 lbs (500 kg) and are further categorized based on mass as shown in **Table 1**.

Table 1: SmallSat Mass Classification

SmallSat Classification	Mass (kg)
Minisatellite	100-500
Microsatellite	10-100
Nanosatellite (includes CubeSats)	1-10
Picosatellite	0.1-1

The focus of this article is on *CubeSats,* a subclass of nanosatellites with heretofore almost unimaginable capabilities, given their small size. Generally, reducing size brings with it attendant limitations in mass, power, maneuvering fuel, communications systems, computational capabilities and, most notably, sensor payloads. But despite these apparent limitations, CubeSats have eminent utility for Earth system science studies, as the pages that follow will reveal.

[1] This was a nickname for the early large-platform concept. The origin was indicative that these designs were not in keeping with then-NASA Administrator Dan Goldin's desire for "faster, better, cheaper" approaches for NASA.
[2] For detailed background on the early days of EOS, see *The Earth Observer: Perspectives on EOS Special Edition*, downloadable from *https://go.nasa.gov/2Jciu0X.*

CubeSats: Physically Limited, Scientifically Expansive

Since 2012 NASA's Earth Science Technology Office (ESTO) and Earth Science Division have funded and fostered many CubeSat missions, each aimed to demonstrate a new technology to better monitor Earth and, in several cases, augment data acquired through other missions.

Table 2. NASA-funded Earth Science CubeSat missions, their scientific foci, technologies, and status.

CubeSat*	Lead Organization	Science	Technology	Launch Date and Status
CIRiS-BATC	Ball Aerospace	Land and Sea Surface Temperatures	Highly calibrated uncooled bolometer infrared sensors	December 5, 2019 – In operation
CSIM	University of Colorado, Laboratory for Atmospheric and Space Physics (LASP)	Solar Irradiance	Compact infrared radiometer with onboard calibration	March 12, 2018 – In operation
CTIM	University of Colorado, LASP	Solar Irradiance	Room-temperature vertically aligned carbon nanotube (VACNT) bolometers	TBD – In development
CubeRRT	Ohio State University	Radio Frequency (RF) Interference	Wideband antenna, radiometer front-end, and digital back end	May 21, 2018 – In operation
HARP	University of Maryland, Baltimore County	Cloud and Aerosol Properties	Wide field-of-view imaging polarimeter	November 2, 2019 – In operation
HYTI	University of Hawaii	Thermal Hyperspectral Imaging	Fabry-Perot interferometer, hyperspectral thermal imager	TBD – In development
IceCube	NASA's Goddard Space Flight Center	Cloud Ice	Submillimeter wave imaging radiometer	April 18, 2017 – Mission complete
IPEX	NASA/Jet Propulsion Laboratory (JPL)	Autonomous science and product delivery	Near-real-time, low-latency autonomous product generation	December 5, 2013 – Mission complete
NACHOS	Los Alamos National Laboratory	Atmospheric Trace Gases	Ultracompact, high-resolution, hyperspectral imager	TBD – In development
RainCube	JPL	Atmospheric Moisture Distribution	Compact K_a-band radar	May 21, 2018 – In operation
RAVAN	Johns Hopkins University Applied Physics Laboratory	Solar Radiation	Miniaturized radiometer with carbon nanotubes bolometer	November 11, 2016 – Mission complete
SNoOPI	Purdue University	Soil Moisture	Opportunistic P-band signals as proxies for moisture levels	TBD – In development
TEMPEST-D	Colorado State University	Atmospheric Moisture Distribution	Scanning RF Radiometry imager	May 21, 2018 – In operation

* Acronyms used in Table 2. ***CIRiS-BATC***—Compact Infrared Radiometer in Space-Ball Aerospace Technology Company; ***CSIM***—Compact Solar Irradiance Monitor; ***CTIM***—Compact Total Irradiance Monitor; ***CubeRRT***—CubeSat Radiometer Radio Frequency Interference Technology Validation; ***HARP***—Hyper-Angular Rainbow Polarimeter; ***HYTI***—Hyperspectral Thermal Imager; ***IceCube***—not an acronym; ***IPEX***—Intelligent Payload Experiment; ***NACHOS***—NanoSat Atmospheric Chemistry Hyperspectral Observation System; ***RainCube***—Radar in a CubeSat; ***RAVAN***—Radiometer Assessment using Vertically Aligned Nanotubes; ***SNoOPI***—SigNals of Opportunity: P-band Investigation; and ***TEMPEST-D***—Temporal Experiment for Storms and Tropical Systems - Demonstrator.

Several representative NASA-funded CubeSats are listed in **Table 2** on page 6. Space limitations preclude including details of the technologies being used, but the descriptions of the CubeSat names (listed in the table) give ample testimony of the incredible range of technologies and sciences being addressed by these platforms and their payloads. A full list of NASA-funded SmallSats and CubeSats may be found at *https://go.nasa.gov/3nNThsm*. Discussion of real-world results from some of these missions is found in "Some CubeSat Earth Science Contributions" on page 10.

Although beyond the normal context for *The Earth Observer*, it is worth noting that CubeSats are also enjoying increasing popularity in the other divisions of NASA's Science Mission Directorate. This is further evidence that small size does not equate with small scientific return. **Table 3** lists several examples of space and space-related missions that are being handled by these miniature marvels of technology.

The CubeSat concept was created in 1999 by researchers to help university students launch their inventions into space with very stringent volume, weight, power, and—of course!—cost constraints.

Table 3. NASA-related Nonterrestrial CubeSat and SmallSat Missions.

Mission Focus	Mission*	Discipline Area	Technology
Planetary	MarCO	Telecommunications	Mars Insight lander communications relay constellation
	LunaH-Map	Potential lunar water locations	Compact neutron spectrometer
Astrophysics	SPRITE	Measure shocked gas in Magellanic Cloud remnants	Compact UV-imaging spectrograph
	BurstCube	Gravitational waves and counterparts	Silicon photomultiplier scintillator detectors
	BlackCat	High-energy celestial events	X-ray hybrid CMOS detectors
	HaloSat	Explore Milky Way's hot-gas halo	XR-100SDD-X X-ray detectors
Heliophysics	SunRISE	Giant solar particle storms	Radio telescopy constellation
	Elfin	Relativistic electron fluxes	Fluxgate magnetometer and energetic particle detectors

* Acronyms used in Table 3. ***MarCO***—Mars Cube One; ***LunaH-Map***—Lunar Polar Hydrogen Mapper; ***SPRITE***—Supernova Remnants/Proxies for Reionization/and Integrated Testbed Experiment; ***BurstCube***—derives from its target of gamma ray bursts; ***BlackCat***—Black hole Coded Aperture Telescope; ***CMOS***—complementary metal oxide semiconductor; ***HaloSat***—derives from its mission to explore the Milky Way's hot-gas halo; ***SunRISE***—Sun Radio Interferometer Space Experiment; and ***Elfin***—Electron Losses and Fields Investigation.

The focus of the remainder of this article will be on how NASA came to adopt and adapt CubeSats for Earth science activities and some thoughts on the future of these noteworthy constructs.

CubeSat Origins

The CubeSat concept was created in 1999 by researchers to help university students launch their inventions into space with very stringent volume, weight, power, and—of course!—cost constraints. **Bob Twiggs**, then a professor at Stanford University, and **Jordi Puig-Suari**, an engineer at California Polytechnic State University (Cal Poly), wanted students to have hands-on experiences building and launching functioning satellites while keeping overall costs low.

In an interview with *Spaceflight Now* in 2013, Twiggs said that he was inspired to develop the CubeSat because of Beanie Babies, the enduring line of stuffed toys. More specifically, he was inspired by the size and shape of their containers. It seems that the size, standardization, and ease of storage implemented for these toys were all important factors in bounding his own problem.

The first CubeSat Twiggs and his collaborators and students launched was QuakeSat, designed to help detect earthquakes. QuakeSat was launched in June 2003 from Russia's Plesetsk launch site and survived for just over seven months. While lifetimes for current platforms are—by design—usually on the order of six months or so, several, including the NASA-supported RainCube and Temporal Experiment for

Storms and Tropical Systems - Demonstrator (TEMPEST-D; see Table 2) have been in orbit, performing their assigned tasks, for two years.

This is not even a record: Focused Investigations of Relativistic Electron Burst Intensity, Range, and Dynamics (FIREBIRD) is a National Science Foundation-funded effort implemented by the University of New Hampshire (which designed and built the FIRE component with two solid-state detectors) and Montana State University–Bozeman, responsible for the BIRD component (which controls power and communications between FIRE and the ground). Four FIREBIRD 1.5U CubeSats, deployed in pairs in two separate launches, were designed to resolve the spatial-scale size and energy dependence of electron microbursts emanating from the Van Allen radiation belts. The FIREBIRD II mission was launched in January 2015. One satellite failed after four-and-a-half years due to an internal short in a battery, but its twin is still operating, approaching six years of continuous operation.

NASA's Early CubeSats

When they were first introduced, there was a lot of skepticism in the science community that these tiny, relatively inexpensive, seemingly toy-like satellites could obtain valuable Earth observations.

At first, CubeSats were not taken seriously by many scientists and technologists. When they were first introduced, there was a lot of skepticism in the science community that these tiny, relatively inexpensive, seemingly toy-like satellites could obtain valuable Earth observations.

However, NASA investigators can be a forward-looking bunch. Take for example, **John Hines**, at NASA's Ames Research Center, who saw significant opportunities in small satellites and initiated a mission that became the forerunner for miniaturized missions.

As a result of Hines' initiation—and his having formed a solid team—December 16, 2006 saw the launch of GeneSat-1 from NASA's Wallops Flight Facility (WFF) on a Minotaur launch vehicle. Weighing in at 11 lbs (5 kg), heavier than the now-standardized CubeSat specification (discussed later), this orbiting bacterial genetics laboratory included miniaturized analytical instrumentation, bacterial life support, and an ultra-high-frequency beacon for tracking purposes. This mission was the result of collaboration between NASA, the private sector, and academia. With the success of GeneSat-1, NASA's continued interest in such facilities was primed for growth.

By 2012 the potential for CubeSats began to be clearly recognized across many scientific disciplines. In the realm of Earth sciences, the panoply of scientific disciplines that could be affected included atmosphere, land, ocean, snow and ice, and geophysical sciences, e.g., gravity and magnetic fields.[3] Such potential was realized on December 5, 2013, with the launch of the Intelligent Payload Experiment (IPEX), a true *standardized* (as defined in the next section) CubeSat developed by Cal Poly and the NASA/Jet Propulsion Laboratory (JPL). IPEX[4] was largely a technology development and demonstration mission to provide applicable data that would affect the design of data-handling infrastructure for JPL's Hyperspectral Infrared Imager (HyspIRI) mission.[5]

It was also clear that CubeSats could be used, for example, to support disaster monitoring and response management and, over time, other applications began to become candidates for CubeSat-derived data—just like their larger cousins. Because of their relatively low cost and other related factors, CubeSats could provide supporting, correlative data for their larger precursor missions and could allow implementation of relatively inexpensive, constellation-based missions, bringing the benefits of such mission design to a wider range of investigations and applications.

[3] For a comprehensive, forward-looking survey of such potentialities, download the document at *http://systemarchitect.mit.edu/docs/selva12b.pdf*.
[4] Additional information on IPEX may be found at *https://go.nasa.gov/39hLJtY*.
[5] For more on HyspIRI, visit *https://hyspiri.jpl.nasa.gov*.

Hundreds of organizations worldwide, including NASA, have now built, launched, activated, and used over 1000 CubeSats.[6] A key feature is that the tiny satellites are helping researchers and funding agencies lower the risks and barriers to entry that researchers typically face when they want to try something new and ambitious, like shrinking a working radar to CubeSat dimensions—as has been done (see RainCube on page 14).

Hundreds of organizations worldwide, including NASA, have now built, launched, activated, and used over 1000 CubeSats.

Such statements aside, how can anyone unfamiliar with their characteristics and capabilities understand CubeSats' growing popularity? To address this before providing examples of their utility, a short primer on CubeSats is provided.

Standardizing Specifications and Procedures

As alluded to earlier, there have been several forces leading a drive toward standardization of CubeSat designs—a move that has had clear benefits to the CubeSat community.

Operational definition of a CubeSat comes from adherence to the CubeSat Design Specification.[7] The standard was developed by the CubeSat Program at Cal Poly[8] and is continually updated by that group in consultation with organizations worldwide, including government agencies, universities and other educational institutions, and representatives of the private sector. It is the *de facto* specification for CubeSat development and implementation, and failure to conform to these standards will prevent implementation downstream from this review point—e.g., not conforming to launch form-factor and environmental constraints will cause immediate elimination from consideration for further activities by cognizant regulatory groups and launch-providers (e.g., NASA).

A primary driver for standardization comes from the way CubeSats are launched as secondary payloads on larger missions—see *Finding a Launch Opportunity* on page 12. For primary-mission safety and integrity, a means had to be found to prevent any impact from CubeSat launches on that primary payload.

This resulted in the Poly Picosatellite Orbital Deployer (P-POD), as shown in **Figure 1**. The P-POD is, basically, a rectangular box of defined size with a spring-loaded pusher plate to eject the CubeSat(s). The loaded P-POD is installed on a space-available basis as a secondary payload on larger-satellite launches. Thus to minimize any impact on the primary payload and the launch vehicle, the P-POD defines the basic shape for CubeSats and, as a result, significant boundary conditions on payloads and infrastructure.

Figure 1. Poly Picosatellite Orbital Deployer (P-POD). Note the relative simplicity of the design, implementing what is basically a spring-forced plate that pushes the CubeSats out of the P-POD and into orbit. **Image credit:** Cal Poly

While there are such real-world limits, engineers and technologists are usually not prevented from creative solutions that still conform to constraints. Over time, developers realized that the basic CubeSat form factor could be parlayed into designs that would still conform to the P-POD requirements, but with expanded sizes *in one dimension*: length. A capability to "stack" CubeSats developed, such that with a standard cube, referred to as a single *unit* (1U); it is now common to have form factors that range from 0.5U to 12U. More on *units* is found in the next section.

[6] Learn more about the numbers and types of nanosatellites—including CubeSats—at *https://www.nanosats.eu*.

[7] See, for example, *https://www.cubesat.org/s/cds_rev13_final2.pdf,* for specifications for these platforms. Note that Rev. 14 is currently in draft form and available for review and comment from *https://www.cubesat.org/cds-announcement.*

[8] For more on Cal Poly's CubeSat Program, visit *https://www.cubesat.org*.

But while the satellites must conform to this form factor at launch, there is nothing in the CubeSat Design Specification that says they cannot expand their volume once on orbit. For instance, Radar in a CubeSat, or RainCube, has a deployable antenna that unfurled after it was deployed from the International Space Station on May 21, 2018. RainCube was the first CubeSat to demonstrate an active measurement of rainfall within storms, in this case by radar—see "Some CubeSat Earth Science Contributions" on page 13.

As a side note, there are other SmallSats—usually from the private sector—that do not conform to the CubeSat standard, but are available for commercial use, using launch technology that is similar to the P-POD in function but not in design. There are no standards for these technologies.

Size, Weight, and Power Specifications

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As shown in **Figure 2**, each basic CubeSat has a form factor of 3.9 x 3.9 x 3.9 in (10 x 10 x 10 cm) and weighs up to 4.4 lbs (2 kg). CubeSats are measured by how many of these blocks, or units (U), they use. Within (or attached to the surface of) that volume must be included all requirements for spacecraft utility, including avionics and onboard data handling, attitude determination and control, communications, power, propulsion, and thermal control. Examples of 1U and 3U CubeSats are shown in **Figure 3**.

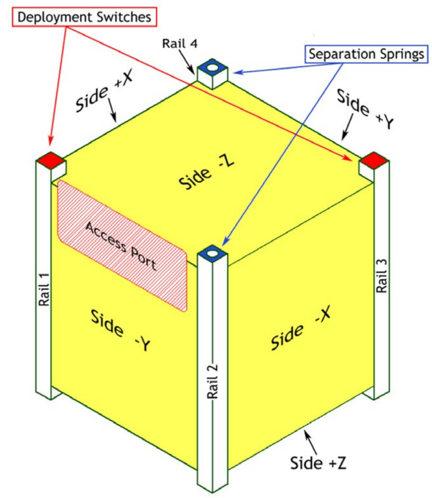

Figure 2. Isometric representation of a CubeSat's physical envelope. **Image credit:** Cal Poly

Figure 3. Comparison of 1U and 3U CubeSats. **Image credit:** Cal Poly

Virtually every aspect of the requirements basic to all satellites has been miniaturized. For example, attitude control, whether by reaction wheels or—in many cases, owing to the low inertia of these small constructs—existing forces, e.g., alignment with Earth's magnetic field, may be pressed into service in unique ways.

Perhaps more of an engineering challenge than the miniaturized technology itself is the requirement for some missions to have maneuvering capability: Gases are commonly used as a propellant on larger platforms; however, such use in a CubeSat is problematical since there is not much room within the confines of the cube for a potentially useful reservoir. Other maneuvering modes, such as ion propulsion, have more "oomph" with a CubeSat than with a larger sibling due to its smaller inertia, and therefore become viable candidates for attitude adjustment, realizable on the miniaturized scale needed by CubeSats.

Electrical power for satellite health and payload support is another limiting factor. Batteries can only last so long—even those with newer chemistries (e.g., lithium ion), which normally have longer lifetimes, may be limited by the cold soak of space. Solar panels are another option, but they must be kept pointed toward the Sun (requiring station-keeping or attitude-adjustment fuel) and kept tightly folded against the satellite at launch so as not to exceed the P-POD envelope requirements—and they have to unfold and work, adding more mechanisms and concomitant complexity that must be kept within the mass and volume constraints.

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In addition to just keeping the payload operating, data handling (e.g., recording and storing) and telecommunications (e.g., command and control and data transfer) all must be accommodated within the very stringent constraints. Designs must include response to the requirement that CubeSats only transmit their data when they pass over a specific ground station, for instance, the one located at WFF.

The Care and Feeding of CubeSats: Practicalities

While watching a tall, elegant launch vehicle soar into the sky is especially thrilling when you know that among its passengers are tiny CubeSats on specific missions to prove new, potentially groundbreaking technologies offering new ways to observe Earth from space—getting to that stage takes a lot of hard work! Problems and issues can arise throughout the entire process, from designing and building a CubeSat, to ensuring that it is ready and able to launch, to keeping it working and able to send back data while in orbit.

This section describes several examples of "what's behind the curtain" for a successful CubeSat mission, including CubeSat provider responsibilities, practical problems in designing and building a CubeSat, finding launch opportunities, and orbital operations.

CubeSat Provider Responsibilities

In addition to having to meet all SWaP requirements outlined elsewhere, CubeSat providers must conform to other absolute requirements, not only to ensure proper function of their platform, but also to prevent deleterious impact on launch systems and other payloads, whether mechanical, electrical, or from contamination.[9]

Furthermore, NASA CubeSats must conform to all NASA launch requirements, particularly as regards safety. These requirements address not just the physical envelope and P-POD requirements, but also mandate safety—e.g., there are to be no pyrotechnics used and there is to be limited outgassing. Thermal vacuum and vibrational testing may also be needed—indeed, any test may be called for by cognizant launch authorities to demonstrate the physical integrity of the smaller payload, not least to ensure no deleterious effects on the primary.

[9] "CubeSat 101," an introductory but in-depth look at getting started with CubeSats, may be downloaded from *https://go.nasa.gov/2GH86rL*.

In addition, all CubeSats (not just NASA-funded) must comply with orbital debris mitigation requirements and have an Orbital Debris Assessment Report or similar document, to ensure that a CubeSat will not interfere with another orbiting spacecraft, will deorbit in a reasonable amount of time, and will not survive reentry into the atmosphere. In addition to NASA's own, such requirements are also levied by the Federal Communications Commission and the National Oceanic and Atmospheric Administration (NOAA).

Overcoming Problems in Designing and Building a CubeSat: Lessons from HARP

NASA's Hyper-Angular Rainbow Polarimeter (HARP) CubeSat is currently operating in orbit, but some major issues could have terminated the mission.

In an attempt to keep costs low while packing a lot of scientific capabilities into the CubeSat, the team used commercial off-the-shelf (COTS) parts and found out that some of those parts were not able to handle the demanding environment of space, which they recreated with a thermal vacuum chamber.

The team also had to decide what scientifically viable, useful data they wanted to collect and what the tiny spacecraft was actually capable of doing. HARP was launched from WFF in November 2019. It is a 3U CubeSat and NASA's first attempt to put a polarimeter aboard a CubeSat. That attempt and the data choices have borne fruit: HARP is collecting vital information about clouds and *aerosols*, tiny particles in the atmosphere that can act as nuclei on which cloud droplets and ice particles form. These measurements help us better understand how aerosol particles impact weather, climate, and air quality. Despite some compromises, HARP is a viable adjunct to Earth science studies.

Finding a Launch Opportunity

Mission-nonspecific launch opportunities are traditionally tricky to secure for spacecraft developers and operators as there are attendant costs besides the monetary ones. As a result, CubeSats are at both an advantage and a disadvantage. On their own, they are not big enough to command their own launch vehicles, but they can easily hitch rides whenever there's room or—occasionally—form a "quorum" to command a rocket dedicated to SmallSats.

When researchers first started launching CubeSats, only a few rockets were able to fit them into their typical payload spaces. Now virtually all launchers include CubeSats when they have room, and such opportunities appear to be increasing, both as to number and orbital destination. There have also been missions where the entire focus was on small satellites. For example, on December 3, 2018, SpaceX launched its Falcon 9 rocket booster with 64 small satellite passengers from Vandenberg Air Force Base (VAFB) in California. The mission, titled "SSO-A SmallSat Express," included 49 CubeSats and was the first mission dedicated for small payloads to a sun-synchronous orbit.

NASA sees the potential for CubeSats as being so high that it has established the CubeSat Launch Initiative (CSLI) to help schools, universities, and small businesses explore the potential of the CubeSat space by providing an excellent primer with links to actionable sites, some with clearly educational applications.

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Overcoming Operational Problems: Lessons from CSIM

The experience of the NASA-supported Compact Solar Irradiance Monitor (CSIM) CubeSat team, based at the Laboratory for Atmospheric and Space Physics (LASP) at the University of Colorado Boulder, conveys not just the potential for but also the experience of dealing with operational problems with CubeSats.

As discussed earlier and as is the case for larger platforms, preparing satellites for space requires a lot of testing to deal with issues like cosmic particles and the deleterious

[10] For more on CSLI, visit *https://go.nasa.gov/2IjXNdG*.

effects they have on electronics. But resource constraints—primarily cost—preclude such "niceties" for CubeSats that are routine and required for larger, heritage platforms, leaving CubeSats susceptible to cosmic particles. Fortunately, the effects of the cosmic particles are generally not in themselves catastrophic, and the equivalent of a simple reboot can bring the satellite back to working condition. Other such relatively easy fixes have been effective. But space is a tricky operating environment, and CubeSat operators are at the mercy of random events or coincidence.

In the CSIM incident, soon after reaching orbit an unattributed event caused the telecommunications system's SD card, similar to one in a cellphone, to become unusable, causing the CubeSat to lose connection to its team.

Erik Richard [LASP—*CSIM Principal Investigator*] noted: "We just sat there and waited and waited and waited until one day I got an email from a ham radio guy in New Zealand. He said, 'Hey! I just started seeing [receiving signals from] beacons from your satellite.'" Later that same evening (on January 31, 2019) Richard headed into the laboratory with a colleague and was able to similarly locate their tiny satellite as it passed over Boulder and thereafter commenced operations.

Backups come with impacts—both positive and negative—but CSIM has been running on its backup SD card for a little over a year. Since the electronics are at a higher risk from cosmic impact when they are in use, the team enables the system only when there are enough data to send back to Earth.

A Sharing Economy

The increasing popularity of CubeSats has resulted in a *sharing community*, through which designers, builders, and operators can access lessons learned, tips, and responses to requirements, sharing relevant, actionable knowledge freely. Because of the requirement for envelope specifications forced by the use of the P-POD launcher and with the discovery over time that sharing ideas, concepts, and structures—indeed, most of what a small satellite needs to function—would reduce overall costs to individual groups using this technology, specifications further became an absolute requirement. Standardization and the growing eagerness of the CubeSat community to share resources have led to CubeSats becoming the *Legos*™ of satellites, in that components may be COTS products—or custom made—and shared between groups. This allows the basics of a plug-and-play development approach, allowing more-advanced, mission-specific technologies to be integrated into what could be considered a common bus.

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The vibrancy of this community is reflected in meetings like the Small Satellite Conference (*https://smallsat.org*) held in Logan, UT, annually in August, and the CubeSat Developers Workshop (*https://cubesat.org*) held annually in April in San Luis Obispo, CA.

Some CubeSat Earth Science Contributions

All the preceding was presented to demonstrate that CubeSats—while seemingly impossibly small to be of any real scientific or technological use—deserve scientific and technical respect, as demonstrated by their growing track record of acquiring useful scientific data.

In Earth science work, not only are CubeSats providing significant data on and of their own, as described throughout this article, but their data are also useful to support other missions. For example, the earlier-described CSIM is measuring spectral solar irradiance, which provides insight into how the Earth's atmosphere responds to changes in solar output. Its data are comparable to those from NASA's Total and Spectral Solar Irradiance Sensor (TSIS-1), currently aboard the International Space Station.

feature article

RainCube

The NASA-supported RainCube and TEMPEST-D CubeSats (see Table 1) are able to measure rain and clouds during storms, supporting information collected by the Global Precipitation Mission (GPM) and NOAA's Geostationary Operational Environmental Satellite—Series R (GOES-R) satellites (GOES-16 and -17), and other weather satellites. RainCube was launched from the ISS on June 25, 2018. Using a 35.75-GHz (K_a-band) radar, this mission demonstrated for the first time that it is possible to make a radar measurement from a CubeSat, as shown in **Figure 4**. TEMPEST-D is part of Orbital ATK's OA-9 Cygnus resupply mission that launched from WFF on May 21, 2018.

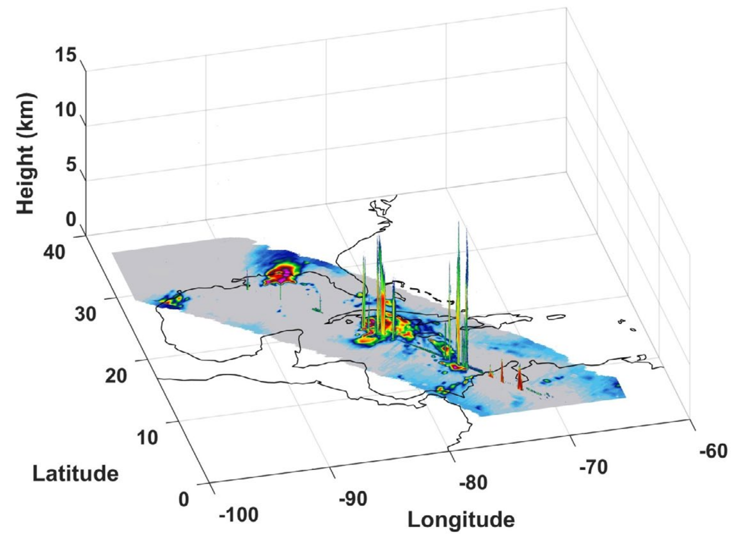

Figure 4. Two CubeSats captured data showing how Tropical Storm Laura strengthened (center of image, south of Cuba) while Tropical Storm Marco (center left of image, coastal U.S.) made landfall on August 24, 2020. CubeSats TEMPEST-D and RainCube recorded how the clouds changed and how much rain actually fell. RainCube measures 3-D vertical profiles of rainfall intensity, while TEMPEST-D provides 2-D horizontal slices of data (clouds and precipitation processes) at different altitudes, providing a unique look inside these storm systems. Both CubeSats have been in operation for two years. **Image credit:** NASA

IceCube

The 3U IceCube CubeSat, led by a team at NASA's Goddard Space Flight Center (GSFC), showed scientists a new way to study high-flying clouds to better understand their unique effect on Earth's climate. It was successfully deployed from the ISS on May 16, 2016. Its onboard radiometer produced the first global atmospheric ice map using an 883-GHz radiometer specifically tuned to study ice clouds in the middle and upper troposphere—see **Figure 5**.

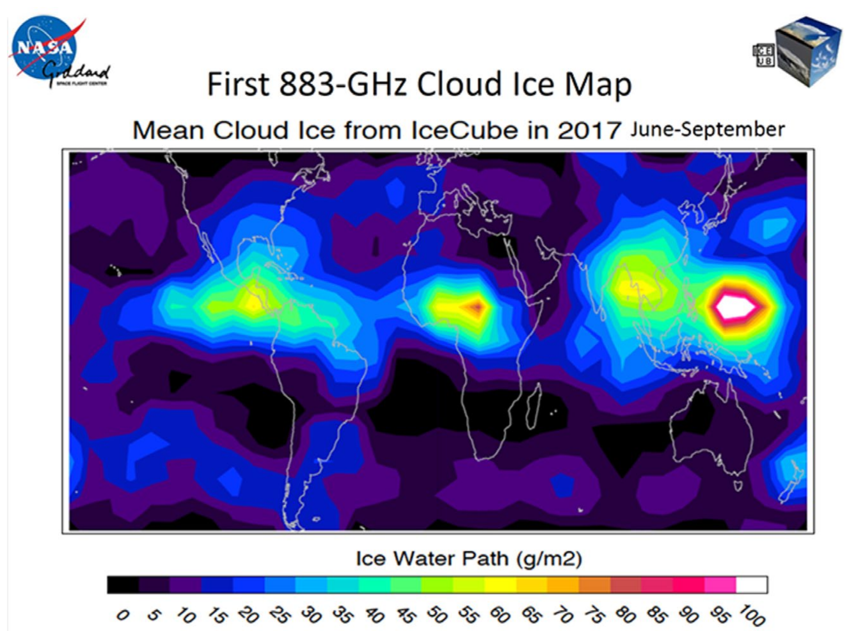

Figure 5. This map is the first-ever global atmospheric ice map at the 883-GHz band, an important submillimeter wavelength frequency for studying cloud ice and its effect on Earth's climate. The white peak areas represent the largest concentration of ice clouds; they are also the spots with heavy precipitation beneath and reach up to the top of the troposphere due to deep convection, which is normally strongest in the tropics. The Ice Water Path, the unit shown in g/m^2, is the integrated cloud ice mass above ~8 km in the troposphere. **Image credit:** NASA

Microwave Radiometer Technology Acceleration

The Microwave Radiometer Technology Acceleration (MiRaTA)[11] CubeSat (see **Figure 6**) is a technology demonstration and test mission to validate new low-power, small-size microwave radiometers, along with a new GPS subsystem needed to take atmospheric sounding measurements by tropospheric radio occultation.

CubeSats can also support larger satellites by flying in a *constellation*, or train, to capture more frequent data to better monitor natural events, e.g., a volcanic eruption, as they unfold. For example, MiRaTA helped inspire the upcoming Earth Venture mission, Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS),[12] a constellation of 3U CubeSats ostensibly scheduled for launch in 2022 that will take rapid-refresh microwave measurements over the Tropics to characterize the thermodynamics and precipitation structure of storm systems across meso- and synoptic scales.

Although the MiRaTA CubeSat failed soon after reaching orbit after launch in November 2017, it provided more than a modicum of success in that investigators noted that much of the technology in MiRaTA paved the way for TROPICS.

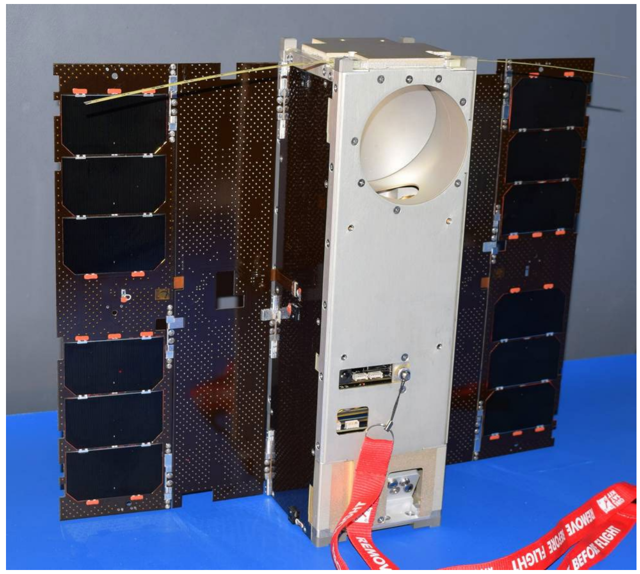

Figure 6. The 3U Microwave Radiometer Technology Acceleration (MiRaTA) satellite with solar panels fully deployed. The circular aperture at the top is for the microwave radiometer antenna. **Image credit:** Massachusetts Institute of Technology Lincoln Laboratory

NASA's Ongoing and Future Support for CubeSat Technology Advancement

NASA's investment of significant resources in CubeSats and related technology is ample evidence that there is a strong and valuable future for them. Several examples of relevant activities follow.

In-Space Validation of Earth Science Technologies

NASA's In-Space Validation of Earth Science Technologies (InVEST) Program is at the forefront of testing and preparing Earth observing sensors for space aboard CubeSats. InVEST funds investigators from academia, industry, and government agencies to demonstrate new measurement capabilities that could advance technology and potentially lead to science missions.

The InVEST program, which oversees many of NASA's Earth Science CubeSats, also oversees instrument technology programs that aim to demonstrate how investment in these miniature technological wonders contributes to larger-scale missions, with technology development having been incorporated into missions that are part of NASA's Earth Venture Program, an element within NASA's Earth System Science Pathfinder Program (ESSP). Earth Venture funds missions that are science-driven, competitively selected, and low cost. Using technologies and data derived from CubeSats allows researchers to obtain more temporally frequent science measurements and can keep costs down.

InVEST is responsive to the science focus areas set forth in the 2007 Earth Science Decadal Survey Report.[13] As a result, InVEST selected four CubeSats as part of its first

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[11] To learn more about the MiRaTA CubeSat, visit *https://beaverworks.ll.mit.edu/CMS/bw/projectmirata*.

[12] For more information on TROPICS and its reliance on CubeSat constellation technology, visit *https://tropics.ll.mit.edu/CMS/tropics*. Also see "Second TROPICS Applications Workshop Summary" in the September–October 2020 issue of *The Earth Observer* [**Volume 32**, **Issue 5**, pp. 15–20, *https://go.nasa.gov/33jMb6W*].

[13] The 2007 Earth Science Decadal Survey was the first in the ongoing series. It was called "Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond" and can be downloaded from *https://www.nap.edu/catalog/11820/earth-science-and-applications-from-space-national-imperatives-for-the*.

solicitation in May 2013. One of those tiny satellites is the Radiometer Assessment Using Vertically Aligned Nanotubes (RAVAN), a 3U CubeSat, successfully launched in November 2016 as a secondary payload on a United Launch Alliance Atlas-V 401 from VAFB to measure Earth's radiation imbalance. In the process, it demonstrated two technologies that were never before used on an orbiting spacecraft: carbon nanotubes that absorb outbound radiation and a gallium phase-change blackbody for calibration.

Instrument Incubation Program

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NASA ESTO's Instrument Incubation Program (IIP) helps investigators imagine new ways to miniaturize and advance sensors so that they can be integrated onto CubeSats, other small satellite platforms, and larger missions. The IIP fosters high-science-quality instruments with relatively low overall costs and reduced development risks for future satellite missions.

In response to recent solicitations[14] for new projects, the program has funded novel lasers, spectrometers, and radars, among other sensors, that are smaller, more affordable, and able to incorporate greater onboard intelligence to take advantage of the tremendous strides in algorithm development and processing power. Instruments incorporating emerging technologies offer the potential to advance technology and science.

In addition to encouraging investigators to test their instruments in laboratories and test chambers, the IIP also sees its investigators test instruments aboard aircraft. For instance, the team behind the CubeSat Imaging Radar for Earth Science (CIRES) IIP project flew multiple flights above the Kilauea Volcano in Hawaii Volcanoes National Park from July 3-5, 2018, to demonstrate an S-band Interferometric synthetic aperture radar (InSAR), which is able to penetrate through vegetation and reach the ground. A future CIRES spacecraft could pave the way for a constellation of small satellites dedicated to monitoring impacts from volcanic activity, earthquakes, and changes in land surfaces. The flights over Kilauea, among other field tests, helped the team learn what worked and what did not work as they developed the instrument. They were able to optimize CIRES to improve its power management, size, sensor capabilities, and ability to withstand heat. Such techniques will have significant utility in designing and implementing other missions.

CSLI and Educational Launch of Nanosatellites

As noted earlier, NASA's CSLI supports CubeSat missions of all types. To date 29 states are on the roster as having involvement with CSLI: Alabama, Alaska, Arizona, California, Colorado, Connecticut, Florida, Hawaii, Illinois, Indiana, Kentucky, Louisiana, Maryland, Massachusetts, Michigan, Missouri, Montana, New Mexico, New York, North Dakota, Ohio, Pennsylvania, Rhode Island, Tennessee, Texas, Utah, Vermont, Virginia, and Wisconsin.

Further, a NASA CSLI educational initiative, Educational Launch of Nanosatellites (ELaNa),[15] was created by NASA to attract and retain students in the science, technology, engineering, and mathematics (STEM) disciplines through the medium of CubeSat mission design, construction, launch, and operation. Activities under the ELaNa program go back to 2011 and continue to this day.

[14] See, for example, the IIP19 solicitation at *https://go.nasa.gov/3leZGv7*. There is a press release at *https://go.nasa.gov/363u0nQ*.
[15] To learn more on ELaNa, visit *https://go.nasa.gov/3l7RDQo*.

Other NASA CubeSat Outreach Efforts

GSFC is actively helping CubeSats evolve into more-robust platforms suitable for real-world applications outside the classroom as teaching foci. For example, WFF is enabling innovative new missions via value-added services for the CubeSat community.[16]

More broadly, NASA shares its latest CubeSat technology with the public through public outreach events, like Earth Day at Union Station in Washington, DC, and online, through stories posted on *NASA.gov* and highlighted on social media. NASA also hosts press events that feature CubeSats, especially prior to upcoming rocket launches that count CubeSats as passengers.

Furthermore, ESTO regularly features life-sized models of CubeSats and information about their scientific and technological capabilities at scientific conferences like the American Geophysical Union's Fall Meeting, the American Meteorological Society's Annual Meeting, and the Institute of Electrical and Electronics Engineers (IEEE) International Geoscience and Remote Sensing Symposium's Annual Meeting to demonstrate how the tiny satellites are able to capture meaningful information about Earth's processes.

The vibrant and exceedingly willing-to-share CubeSat community forms a key basis for the increasing success of CubeSat programs.

Summary and Conclusion

CubeSats are a relatively new resource in the Earth science investigators' toolkits, demonstrably expanding the types, frequency, and quality of data being obtained by their larger antecedents. Owing to the entire concept and implementation that brings with it severe constraints on SWaP, significant creativity and innovation is under way to further increase their utility—not just for Earth science, but in various potential roles for examination of space phenomena.

The vibrant and exceedingly willing-to-share CubeSat community forms a key basis for the increasing success of CubeSat programs. Between COTS supplies and the eagerness of practitioners to share not only the results of their own investigations into what it takes to make a CubeSat capable of significant performance, but actual hardware and software—something of a call-back to the days of "Shareware" in the personal computing realm—CubeSats are enjoying significant popularity, as every effort is being made to keep costs down while driving utility ever higher. Such practical aspects can only bode well for continuing the already-established ability of CubeSats to support NASA's Earth Science activities.

Acknowledgments

The authors would like to thank **Bob Bauer** [GSFC—*ESTO Deputy Program Manager*], **Sachi Babu** [NASA HQ—*ESTO Technology Program Manager*], and **Dave Klumpar** [Space Science and Engineering Laboratory, Montana State University, Bozeman—*Director*] for their helpful critical comments and suggestions. ■

[16] For more on this activity, download the document at *https://go.nasa.gov/3fzHsmx*.

Leveraging Science to Advance Society: The 2020 PACE Applications Workshop

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Introduction

The Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission represents NASA's next great investment in Earth Science—continuing NASA's legacy of over 40 years of satellite ocean color measurements. Scheduled to launch in 2023, PACE will advance our Earth observing and monitoring capabilities through hyperspectral imaging and multi-angle polarimetry of the ocean, atmosphere, and land ecosystems. PACE will give us an unprecedented view of Earth and will take our home planet's "pulse" in new ways for years to come. Game-changing technological advances will enhance the capabilities of PACE over current Earth observing missions and push back the frontier of our scientific understanding to allow fundamental science questions about atmospheric and ocean processes to be answered and knowledge gaps to be filled. These remarkable advances in foundational science through the PACE mission will also support applied science through innovative practical applications of PACE's novel data products directly benefiting society.

With advanced global remote sensing capabilities, PACE will provide information-rich observations that will contribute to an extended time series of inland, coastal, and ocean ecosystems—observations of which have substantial value beyond foundational science and research. Applied science projects, also known as *applications*, are defined as innovative uses of satellite data to improve decision making and provide practical solutions to societal needs. Applications of PACE data will allow stakeholder and research communities to address our most pressing environmental issues. The global atmospheric and oceanic observations from PACE will directly benefit society across a range of applications focus areas, including marine and coastal resource management, disaster response and mitigation, adaptation to a changing climate, ecological forecasting, ecosystem health tracking, air quality monitoring, and human health assurance.

NASA PACE Applications and Early Adopters

As with many recent NASA Earth Science missions, a key PACE mission component is NASA PACE Applications, established to connect PACE data (and those who process it) with individuals and groups who can use it. NASA PACE Applications directly supports NASA's Applied Sciences Program,[1] and seeks to bring together scientists, policy makers, public health practitioners, and industry professionals to apply PACE data to fulfill practical societal needs. NASA PACE Applications seeks to identify and engage a group of applied researchers—referred to as *Early Adopters*, since they will be future users of PACE data—early in the mission's design and development to ensure that anticipated data products and information delivery mechanisms are optimally primed to maximize the utility and value of PACE observations.

Workshop Overview, Motivation, and Structure

To ensure the PACE mission and the anticipated PACE data products meet the needs and objectives of applied user and stakeholder communities, NASA PACE Applications seeks to build partnerships between data producers and data users. Effective scientific communication and stakeholder engagement are crucial elements to identify novel applications of PACE data and demonstrate their practical benefits to society. Therefore, NASA PACE Applications organized the 2020 PACE Applications Workshop as the first event of its kind to bring together PACE data providers and data users.

Like most meetings held during the COVID-19 pandemic, the meeting took place virtually. While an online meeting cannot replicate a face-to-face encounter, the virtual event, which took place on September 23-24, 2020, allowed for regionally broader and more diverse engagement with the mission than would otherwise have been possible had physical presence been the operational mode. Workshop participants included satellite operators, satellite data users, applications developers, and applications users. The event brought together an international community of academics, government partners at the federal, state, and local levels, and participants from private organizations, including nonprofit and nongovernmental organizations (NGOs). Participants initiated a discussion around the PACE mission and how its anticipated data products may be leveraged to benefit society.

This PACE Applications Workshop was designed to ensure participants had the opportunity to connect, contribute, and collaborate productively. Prior to the event, registrants were polled to share their backgrounds, expertise, interests, and demographics, in order for event creators to facilitate a relevant workshop with engaging conversations.

[1] For more information on NASA's Applied Sciences Program, visit *https://appliedsciences.nasa.gov*.

The two-day workshop comprised two morning and two afternoon sessions, each ranging from 90 to 150 minutes. During the first day's morning session, three 20-minute presentations that introduced the NASA Applied Sciences Program and the PACE mission were followed by an interactive engagement activity, which was effective in welcoming participants and encouraging participation early in the event. Such activities throughout the workshop provided engaging and creative opportunities for the audience to interact with the PACE mission representatives and the workshop hosts and presenters, while providing feedback on community needs and challenges. The three subsequent workshop sessions each consisted of a 30-minute plenary presentation, followed by a one-hour moderated panel and a concluding interactive engagement activity. During the fourth and final session, the participants selected one of three thematic breakout discussions (which are summarized below and focused on *Water-centric*, *Atmosphere-centric*, and *Advanced Topics,* respectively) in place of an engagement activity, to serve as a forum for direct interaction with PACE researchers to discuss how anticipated PACE data products might be applied in novel ways.

The objectives of the workshop were to:

1. provide an overview of the PACE mission and its planned data products;

2. build partnerships between data producers and data users to create channels for feedback and collaboration around how PACE can advance society and fulfill stakeholders' needs;

3. identify challenges in working with satellite data for resource management, disaster response, and decision making among data-user communities; and

4. identify potential applications of PACE data not currently being pursued.

These four workshop objectives were chosen to ensure that the PACE mission's scientific resources and deliverables will be easily and sustainably accessible to stakeholders and to maximize the utility of the PACE mission in support of informed decision making. This workshop summary provides an overview of the materials presented and discussions that were hosted. The content is organized around the four objectives in order to highlight how a creative and diverse set of workshop activities were used to achieve the workshop's themes and goals. The full workshop agenda, speaker biographies, and recordings of the keynote presentations, panel sessions, and engagement activities are available at *https://pace.oceansciences.org/app_workshops.htm*.

Objective 1: PACE Applications, PACE Project Science, and PACE Data

The PACE mission will advance our Earth-observing and monitoring capabilities through hyperspectral imaging and multi-angle polarimetric observations of the ocean, atmosphere, and land as coupled ecosystem components. **Erin Urquhart** [NASA's Goddard Space Flight Center (GSFC)/Science Systems and Applications, Inc. (SSAI)—*PACE Applications Coordinator*] and **Joel Scott** [GSFC/Science Applications International Corporation (SAIC)—*PACE Applications Deputy Coordinator*] cohosted the event and opened each day of the workshop with a brief overview of NASA PACE Applications and the PACE Early Adopter program, both of which serve as mechanisms to build prelaunch partnerships between PACE data producers and data users.

Since this workshop was the first applications-focused event for the PACE mission, communicating NASA's Applied Sciences Program perspectives and providing PACE mission updates was a critical component of the workshop. Three plenary presentations were hosted to provide an overview of the PACE mission and its anticipated data products (i.e., Objective 1).

Woody Turner [NASA Headquarters (HQ)—*Program Manager for Ecological Forecasting*] introduced the NASA Applied Science portfolio and discussed the importance of NASA Applications in supporting societal needs and advancing decision-making capabilities. He explained how the applications workshops and NASA PACE Applications support NASA's capacity-building initiatives and applied-science priorities.

Jeremy Werdell [GSFC—*PACE Project Scientist*] discussed the history of the PACE mission, its current status, and other relevant details about the observatory. He provided an overview of the three instruments that will fly onboard the PACE observatory: the Ocean Color Instrument (OCI), a hyperspectral radiometer being built at GSFC, and two contributed multi-angle polarimeters, the Hyper-Angular Research Polarimeter (HARP2) from the University of Maryland, Baltimore County, and the Spectro-polarimeter for Planetary Exploration (SPEXone) from a consortium of organizations in the Netherlands and Airbus. Werdell also presented a snapshot of the groundbreaking Earth and applied-science capabilities that PACE will enable, including new aquatic bio-optical and biogeochemical retrievals and improved cloud-detection and aerosol retrievals.

Antonio Mannino [GSFC—*PACE Deputy Project Scientist*] provided a summary of PACE OCI, HARP2, and SPEXone data products, processing levels, per-product uncertainties, data availability, and eventual data-access tools. He reported that the PACE mission will provide standard, provisional, and test data products once data acquisition begins. Mannino noted that proxy and simulated OCI, HARP2, and SPEXone datasets are currently being developed.

PACE Research/Strategies Panel

Heidi Dierssen [University of Connecticut (UConn)—*PACE Science and Applications Team Lead*] chaired this session, which hosted five PACE Science and Applications researchers who span aquatic, terrestrial, atmospheric, and modeling fields. Each spoke to their PACE research and their work to develop PACE data products and retrieval algorithms. One of the questions posed to the panelists was: *What data products are you producing for PACE? And how do you envision your PACE research and data products being used by the applied-science community?*

- **Matteo Ottaviani** [Terra Research, Inc.] presented his plans to develop PACE retrieval algorithms for the refractive index for the ocean surface in order to detect, map, and monitor oil seeps and spills to support disaster response and mitigation efforts.
- **Nima Pahlevan** [GSFC/SSAI] discussed his plans to use PACE data to develop aquatic products for freshwater lakes and coastal ecosystems. He is eager to retrieve data on suspended particulate matter and photosynthetic pigments, including chlorophyll-*a*, which occur naturally in phytoplankton, from PACE observations.
- **Cecile Rousseaux** [GSFC/Universities Space Research Association (USRA)] shared her research to leverage PACE's global hyperspectral capabilities to develop algorithms that derive and model phytoplankton properties from a coupled ocean–atmosphere global circulation model (GCM).
- **Snorre Stamnes** [NASA's Langley Research Center (LaRC)] discussed his plans to apply data from PACE's two polarimeters to identify particles in both the atmosphere and ocean and to study Earth from a holistic perspective as a system of interconnected systems.
- **Fred Huemmrich** [University of Maryland, Baltimore County (UMBC), Joint Center for Earth Systems Technology (JCET)/GSFC] encouraged the use of PACE observations to study terrestrial ecosystems, emphasizing that PACE data will be able to characterize plant productivity, identify biological stressors and responses, and describe resource allocations in unprecedented ways via OCI's hyperspectral observations.

Prior to the workshop, the topical leads for the PACE Project Science focus areas (i.e., atmospheric correction, bio-optics, biogeochemical stocks, OCI clouds and aerosols, multi-angle polarimetry, and system vicarious calibration) prerecorded roughly 20-minute presentations introducing their topical areas and how their research supports the PACE mission and PACE Applications. Each presenter gave a brief overview of their interactions with the PACE Science and Applications Teams, algorithm development, testing, and implementation, as well as on the anticipated PACE data products for each focus area. The preworkshop presentations provided background material for the three thematic breakout sessions on the second day of the workshop—summarized in the next section. The six prerecorded presentations can be found online at the website referenced in the Introduction.

Breakout Discussions

In support of Objective 1, the PACE Applications Workshop concluded day two's activities with three parallel thematic breakout sessions, organized by the PACE project science leads. Each breakout session served as a discussion opportunity to learn about the PACE research community's data products and algorithms. When they registered, workshop attendees were able to select which thematic breakout was of most interest to them, and they were able to revisit this decision during the fourth and final session of the workshop. Participants in each thematic breakout section were able to interact with the PACE project science leads and mission personnel who facilitated the discussion. Participants were encouraged to submit questions, engage with each other through the chat dialogue capability of the virtual meeting platform, and respond to polling activities during each thematic breakout discussion. The discussions centered around stakeholders' data needs, product-specific concerns and questions, feedback on coding and data-analysis languages, data-access tools, and brainstorming about potential untapped applications that could create additional utility for PACE data.

Ivona Cetinić [GSFC/USRA], **Lachlan McKinna** [Go2Q Pty Ltd, Australia], and **Ryan Vandermeulen** [GSFC/SSAI] moderated the first thematic breakout discussion, "Water-centric: PACE Biogeochemical Stocks, Pigments, and Inherent Optical Properties (IOPs)." The moderators highlighted several water-centric PACE Early Adopter projects in order to illustrate the PACE mission's capabilities in supporting water-resource management and decision-making activities. The discussion addressed technical topics such as phytoplankton community structure, phytoplankton pigment composition, and hyperspectral coastal retrievals of the photosynthetic pigment, chlorophyll *a*, and other algorithms to improve these types of data retrieval from satellite observations.

Kirk Knobelspiesse [GSFC] and **Andrew Sayer** [GSFC/USRA] moderated the "Atmosphere-centric: PACE Aerosol and Cloud Retrievals" breakout discussion, which explored the atmospheric capabilities of PACE, namely how the three onboard instruments will enable hyperspectral and multi-angular polarimetric retrievals of aerosol and cloud properties and when to use which data source for different applications. Breakout discussion participants provided feedback through a variety of topical polls.

Amir Ibrahim [GSFC/SSAI] and **Susanne Craig** [GSFC/USRA] moderated the "Advanced Topics: PACE Radiometry and Atmospheric Correction" breakout discussion, which provided a short introduction to several advanced PACE-related topics, including an overview of atmospheric correction (AC) and the approaches used to remove the effects of the atmosphere from the surface reflectance signal, radiometry as a set of measurements to derive ocean color and surface properties, and systems vicarious calibration (SVC) plans to ensure steady and accurate radiometric calibration while the PACE OCI sensor is in orbit.

Objective 2: Partnerships, Stakeholder Engagement, and the Associated Challenges

A major goal of NASA PACE Applications is to identify and engage potential user communities in pre-launch PACE mission activities. Therefore, one of the objectives of the 2020 PACE Applications Workshop was to increase partnerships and opportunities for collaboration, discussion, and feedback centered on how PACE can provide practical utility to fulfill societal needs. The workshop served as a venue to connect the PACE science and research communities with stakeholder and decision-maker communities.

From plenary talks to stakeholder panels and interactive polling, the workshop stressed the value of stakeholder engagement—early and often—in applied science projects. As shown in **Figure 1,** ranked on a *Likert Scale*[2] of 1 (strongly disagree) to 5 (strongly agree), and based on engagement-activity responses from 92 participants, not only have they identified their stakeholders (average rank: 3.7), but they also understand their stakeholders' needs (3.4), consider their stakeholders' needs when designing projects (3.9), and actively collaborate with stakeholders (3.5). However, during discussion, it was suggested that perhaps needs are being falsely ascribed to stakeholders or misunderstood by the research community—since the second Likert statement ranked lower than the third and fourth. Both the third and fourth statements implicitly rely on having a comprehensive understanding of stakeholders' needs and cannot be effectively carried out without first having commendably performed statement two: assessing and understanding stakeholders' needs.

Blake Schaeffer [U.S. Environmental Protection Agency (EPA)] gave a plenary presentation sharing insight on and underscoring the value of working with stakeholders throughout the lifecycle of the multi-agency Cyanobacteria Assessment Network (CyAN) project, a multi-agency project that includes the EPA, NASA, USGS, and NOAA. Schaeffer noted that critical differences exist between the features of applied research (e.g., data, figures, statements) and the benefits of applications (e.g., societal advancement, improved decision making). While features are necessary and support the efficacy of the project, he stressed that communicating the benefits and anticipated outcomes of applied research is equally important to gain stakeholder trust and to build sustainable partnerships.

[2] A Likert Scale is a commonly used psychometric scale used for research that involves questionnaires and surveys.

Figure 1. Engagement-activity statements and responses collected during a survey used to assess the level of PACE stakeholder awareness and engagement from September 23, 2020 (total respondents: 92). Numbers are Likert Scale values. **Image credit**: *Mentimeter.com*

Early Adopters Experiences Panel

Maria Tzortziou [City College of New York (CCNY)—*PACE Deputy Program Applications Lead*] moderated this panel, which was intended to showcase practical applications of PACE data to support resource management, public health, and decision-making efforts. Panelists discussed their experiences in engaging application users in their answers to this question: *What are some of the challenges that you have faced when engaging with your user community?*

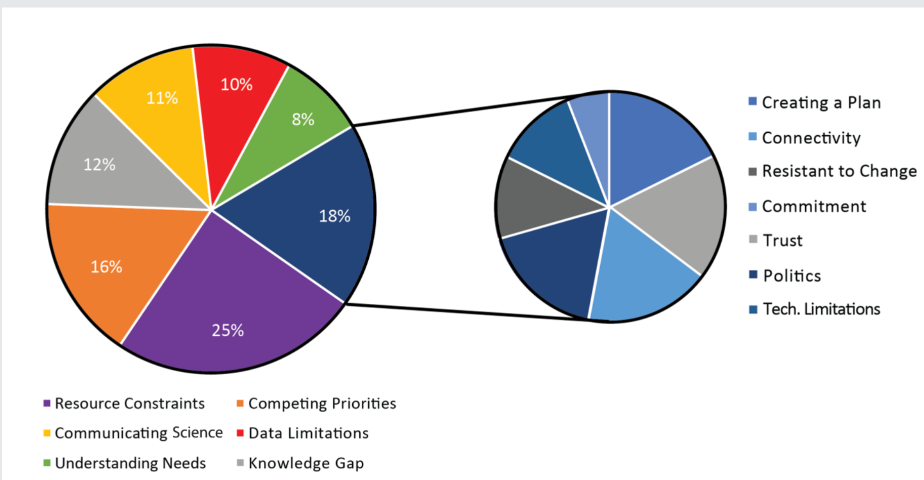
- **Heather Holmes** [University of Utah (UoU)] acknowledged that stakeholders often have limited resources (e.g., funding, time) and reiterated the importance of being considerate of the stakeholders' time and practical needs. Another challenge, broached by the audience in the chat discussion and during the engagement activity, was the difficulty of communicating the accuracy and precision of satellite data to stakeholders.

- **Clarissa Anderson** [Scripps Institution of Oceanography] followed on Holmes' comment about the challenge of communicating uncertainty, adding that "…[users] don't want to see a root mean square (RMS) error or some other metric… rather, nuanced explanations can be more helpful than a concrete metric that is often difficult to interpret."

- **Jordan Borak** [University of Maryland, College Park] spoke about the benefits of setting realistic expectations and not overpromising. He reiterated that while challenging, effective science communication—particularly "listening to stakeholders about their needs" and day-to-day decision making—is crucial to keep discussions active and stakeholders involved.

- **Antar Jutla** [University of Florida (UFL)] highlighted his challenges in working with non-U.S. partners. He noted specifically that: "when working in countries like Mozambique, South Africa, and Bangladesh, the dynamic is really unique. It is a really chaotic process." He added that, "communicating the level of benefit that they [users] can have for their communities and regions is a challenging task."

The pie charts below show that 25% of the participants indicated that resource constraints represent a big challenge in engaging their stakeholders. Other challenges that were mentioned include: competing priorities (16%), knowledge gaps (12%), communicating science (11%), and limitations of the data (10%).



Graphs show challenges in engaging stakeholders and users as identified by the workshop participants.
Image credit: NASA PACE Applications

Despite the daunting list of challenges that were mentioned in working with stakeholders, workshop attendees also shared some of their personal experiences that highlight the benefits of engaging stakeholders early. Several of them emphasized that building a sustained, working partnership with their user and stakeholder communities has many upsides, as the benefits of stakeholder engagement can be reaped as both tangible rewards, as well as in more subtle ways—see **Figure 2** on page 23.

A tangible example of how stakeholder engagement benefits applied-science research projects is that it leads to the creation of more-accurate products, with higher utility as demonstrated by being more widely used by society than others. When a user community's needs are included in the design of data deliverables and products, the products themselves gain greater utility and often achieve broader adoption, perhaps even operationally in support of stakeholders' needs. Stakeholder engagement can provide direct benefits

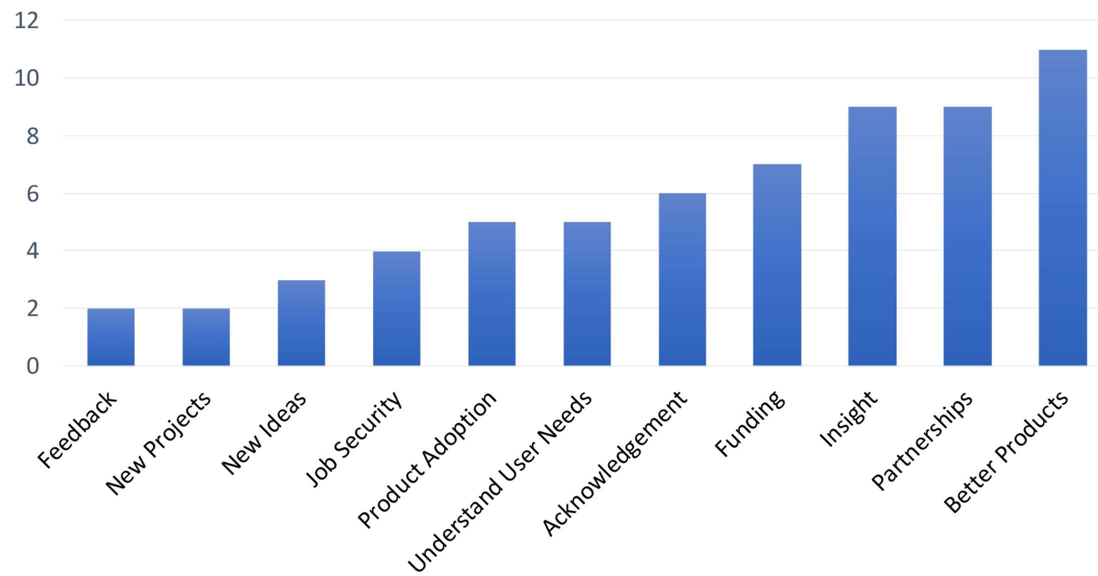


Figure 2. Benefits of stakeholder engagement from the September 23, 2020, engagement-activity responses. **Image credit**: NASA PACE Applications

like acknowledgement, user feedback, or funding opportunities. Both **Woody Turner** [NASA HQ] and **Stephanie Schollaert Uz** [GSFC—*Applied Science Manager in the Earth Sciences Division*] mentioned that many funded research solicitations now encourage—and even require—stakeholder collaboration and engagement at the project-planning and proposal-writing stages.

As noted, there are obvious and directly measurable benefits that may result from engaging and involving stakeholders in applied research, but effective stakeholder engagement also can provide more subtle yet critically important benefits. Stakeholder engagement often leads to working partnerships where feedback can be solicited with new perspectives and insights into another community's needs and experiences. Building lasting partnerships with stakeholders is incredibly important in understanding their needs and can even spawn new ideas and lead to new collaborations and projects. Despite the challenges and obstacles that must be overcome when engaging stakeholders, the workshop attendees agreed that the benefits to applications and the PACE applied and research communities outweigh the hurdles.

Stephanie Schollaert Uz delivered a plenary presentation on NASA Application Readiness Levels (ARLs)[3] and how applied science projects at NASA can leverage this metric to guide and advance their application through the development phases and into a successful, operational context. The nine ARLs can be grouped into three phases: Discovery and Feasibility, Testing and Validation, and Operational Integration, which Uz said, "requires partnerships and, often, agency-level support." She went on to provide real-world examples of NASA ARLs being used to strategically advance applied science projects through a process that begins by "thinking about your unique science and how it can be applied to a societal problem."

There was further discussion about effective stakeholder involvement and engagement approaches during which panelists and workshop participants agreed that keeping initial stakeholder interactions informal (i.e., at professional conferences and meetings) and applying clear, understandable explanations that are free of jargon when discussing science and data products, often proves to be most successful.

Karl Bates [Duke University—*Director of Research Communications*] gave a keynote presentation on the fundamental principles of effective science communication, as both a skill and a crucial tool for connecting the PACE mission with data users, stakeholders, and decision-makers. He emphasized that the key to effective science communication is assessing: *Who are you talking to, what do they know, what do they care about, and what do they find important?* Bates also said that having a succinct, dynamic narrative is a highly effective communication strategy that can be enhanced by preparing anecdotes and storytelling narratives ahead of time. These communication tools strengthen the message when communicating often-complex scientific concepts to a broad audience of varying backgrounds and expertise. Additionally, Bates mentioned that using simple metaphors in place of scientific jargon increases comprehension and maximizes the impact of scientific findings. Effective scientific communication is critical to engaging stakeholders and building lasting partnerships with user communities.

[3] NASA's definitions of Application Readiness Levels can be downloaded from *https://go.nasa.gov/39gviOk*.

Objective 3: Challenges in Using Satellite Data

The third objective of the workshop was to assess the various stakeholder, applied, and research communities' experiences and challenges in discovering, accessing, and working with Earth observation satellite data. This objective aligns closely with one of NASA PACE Application's goals: *To understand applied user and stakeholder experiences and obstacles in discovering, acquiring, and analyzing remotely sensed Earth data*. By assessing challenges pertaining to data access and use, the PACE mission plans to develop data-discovery and data-delivery tools that maximize the utility and availability of PACE data, after launch. Ranked on a Likert Scale of 1 (strongly disagree) to 7 (strongly agree), the 80 engagement-activity responses showed that satellite data are crucial to their work (average rank: 6.5). However, the attendees were split in their opinion as to whether satellite data are easy to use (rank of 7) or hard to use (rank of 1); the average rank among the participants was 4.2. Additionally, 36% of engagement activity participants indicated that current NASA Earth satellite data offerings and products do not meet their needs, as outlined below.

Among the most common complaints from workshop attendees were coarse spatial resolution, inadequate temporal revisit times to support their needs, and high latency between observation and data availability. Other frustrations included missing data due to clouds or algorithm failures, and unclear satellite data precision and accuracy measures. Other feedback related to overwhelming data-discovery portals and technical challenges in processing satellite data. Workshop participants also cited unfamiliar data formats and access tools as obstacles in working with NASA Earth satellite data, often requiring expertise in coding and computer programming.

Stakeholder Stories Panel

Kim Locke [GSFC/ESSIC] moderated this discussion among four individuals who are stakeholders, data users, and decision-makers. She asked each of the panelists to discuss their experience and challenges in using satellite data as a tool to enable and advance their daily work. Below are thoughts they shared when asked: *What are some challenges that you have faced in working with satellite data for managing resources, issuing advisories, or providing guidance?*

- **Federico Hampl** [BioLand, Costa Rica] commented, "for final end-users who aren't super knowledgeable of remote sensing, satellite data are not easy to interpret."

- **W. Scott Pegau** [Oil Spill Recovery Institute] expressed similar sentiments, adding that most end-users, like himself, are not familiar with data processing or programming and analysis languages. Rather, they simply want decision-support tools that enable them to carry out their day-to-day activities.

- **Mindy Sweeny** [Normandeau Associates, Inc.] voiced her issues with data versioning and unexpected changes in satellite-derived products. She stressed that data consistency is crucial for her work with fisheries and marine mammal monitoring.

- **Daniel Inouye** [Washoe County (Nevada) Health District] articulated his challenge with persuading local decision-makers of the importance and utility of remote sensing data, adding that, "a good story can help with educating and empowering decision makers to use satellite data."

These panelists' experiences underscore the importance of remembering that satellite measurements are not intended to replace traditional field and laboratory-based measurements. Rather, satellites offer a complementary approach, augmenting and extending ground-based data.

Antar Jutla [UFL] echoed the challenges raised during the Stakeholder Stories Panel surrounding the value of remotely sensed satellite data and the difficulty in communicating the underlying meaning of the data products. He said that, "stakeholders think remote sensing is going to solve all their problems. It is not."

Heather Holmes [UoU] also noted, "people think satellites are the answer to not having to use high-cost, *in situ* sensors, but there are a lot of places that satellites are struggling to quantify air quality."

During the Atmospheric-centric Breakout, the discussion touched on a number of challenges that arise when working with satellite and remotely sensed data, revealing high interest in local- and regional-scale products, a smaller need for low-latency products, and a request for more information on data gridding, data management, and calibration and validation strategies for the two polarimeters.

Through the dialogues begun at this workshop, the PACE applied, research, and stakeholder communities are engaged in ongoing efforts to assess and understand the challenges that each community faces in working with Earth satellite science data to support their needs. These ongoing discussions are critical to ensuring that all relevant communities' needs and experiences are heard and addressed, especially the needs of the stakeholders, who often feel that their needs and challenges are overlooked by scientific researchers and data producers. The PACE mission is determined to integrate this feedback and continue this type of user-experience dialogue to build collaborative partnerships and address these challenges, while ensuring that future PACE data products have a high level of utility, are accessible, and can be easily leveraged to support decision-makers and broader societal needs.

Objective 4: Novel Applications of PACE Data

One of the desired outcomes of NASA PACE Applications is to identify potential applied-science projects and new applications of PACE data that are not currently being pursued. Novel applied research is sought that leverages the PACE mission's capabilities in unique ways for the benefit of society to create additional value and utility for the mission. The workshop was intended to provide an opportunity to brainstorm these types of ideas with stakeholders and decision-makers, as well as with the PACE applied and research communities. The specific feedback was broken down by application areas (air quality and health, water resources, climate, ecological forecasting, and disasters). Overall, workshop attendees discussed and shared their enthusiasm for a number of ideas that will be assessed for feasibility from PACE data and may potentially be targeted through future PACE Early Adopter projects or applied science capacity-building initiatives.

Current applications activities were a recurring topic of discussion throughout the meeting. During the Advanced Topics Breakout discussion, participants expressed enthusiasm for using PACE data products for water-quality management, for harmful algal-bloom detection, and for operational use in naval planning. Additionally, a number of applied science projects were discussed during the *Early Adopter Experiences Panel* and *Stakeholder Stories Panel,* highlighting health and air-quality monitoring and disaster-response and -mitigation applications. For example, PACE Early Adopter **Heather Holmes's** project to study the impacts of wildfire and mountainous terrain on air quality directly supports **Daniel Inouye's** needs as a stakeholder who monitors air quality and issues health advisories for portions of Utah and the Western United States. Another Stakeholder Stories panelist, **W. Scott Pegau**, hopes to use **Matteo Ottaviani's** [Terra Research, Inc.] research to better detect oil seeps and spills, thereby enhancing response and cleanup efforts.

Workshop attendees noted that health and air-quality needs could further be supported through PACE data—particularly from the two multi-angle polarimeters—in regions beyond the Western U.S. to include fire-prone areas on other continents, e.g., Australia. However, workshop attendees acknowledged that this would require the engagement of local stakeholders and regional air-quality managers.

Another potential application of PACE data is to support human safety and disaster responses through plume injection height retrievals of ash and sulfur dioxide from volcanic eruptions. These materials are harmful to commercial aviation (potentially leading to jet engine failure), and near the surface (where these aerosols and chemical compounds can be harmful to human health if inhaled in high concentrations). PACE data can support detection and mitigation efforts for both of these effects of volcano eruptions through more-accurate plume tracking via parallax analysis of volcano plumes using multi-angle polarimeter PACE observations.

Attendees also mentioned the importance of leveraging anticipated PACE data products to support ecological forecasting, climate, and water-resource needs in a variety of ways. PACE data have the potential to map and assess natural and anthropogenic threats to coral reef ecosystems from climate change, warming and acidifying oceans with more-destructive wave energy, land–water nutrient fluxes, and practices (e.g., overfishing) that are associated with mass coral die-off, often called *bleaching* events. Participants in the Water-centric Breakout discussion asked several questions about the capabilities of the PACE mission to monitor impacts on coastal and coral reef ecosystems, touching on ocean acidification, benthic and shallow water retrievals, and the variability of coastal inherent optical properties. Additionally, participants noted the possibility of PACE data products supporting El Niño–Southern Oscillation (ENSO) phase detection in support of South American fishery management activities. It was also noted that PACE data might support the further study of cross-correlations and covariations between ENSO and other global weather cycles, such as the Indian monsoon, the North Atlantic Oscillation (NAO), and Pacific Decadal Oscillation (PDO). Furthermore, PACE data might also support the detection of environmental pollutants such as plastic and other floating trash, which could aid in clean-up and mitigation efforts to protect marine wildlife and to support healthy beaches and coastal estuaries.

Additional research and application ideas discussed by workshop attendees included a variety of topics pertaining to the land, vegetation, and cryosphere realms. PACE data will be able to monitor vegetative health and nutrient levels of plants and forests, monitor land-use changes, detect deforestation, and support (i.e., provide input for) coupled global models of the carbon cycle by providing terrestrial observations for assimilation into these models. Anticipated PACE data products (e.g., aerosol and cloud retrievals over snow and ice) will also be able to further our understanding of polar regions and the impacts of a changing climate on ice sheets and ocean–ice interface nutrient fluxes and biological activity. Workshop participants also broached the idea of multi-instrument data synthesis from multiple, complementary satellite datasets to enable detailed and smaller-scale land-use change and risk mapping due to coastal erosion and sea-level change, or possibly to strengthen infrastructure management activities by better mapping the risk factors associated with permafrost thaw.

Workshop Recommendations and Feedback

The 2020 PACE Applications Workshop planning committee has conducted a preliminary assessment of this first workshop, which included a synthesis of community comments and of the qualitative responses submitted via the post-event survey. To be responsive to the PACE applied science and user communities, future PACE Applications events will address a variety of topics at the request of attendees.

Workshop participants were inspired by discussions from both the *Early Adopter Experiences Panel* and *Stakeholder Stories Panel* and there was a resounding enthusiasm for future PACE Applications events to feature longer plenary-type presentations on a variety of applied-science projects—focusing on the real-world benefits and the impacts of terrestrial, air-quality, disaster, and coastal applied-research initiatives. Attendees also requested future presentations on stakeholder projects—in particular, focusing on their needs and the utility that remotely sensed Earth data can provide to their work. Furthermore, workshop participants from both data-user and data-producer communities expressed an interest in future tutorial and training events to learn more about what prelaunch proxy and simulated PACE datasets would be available and how best to use them in preparatory and applied research projects to build capacity for postlaunch activities.

Feedback from workshop participants will inform future PACE Applications workshops, focus sessions, and tutorial and training activities. Most notably, participants from this event indicated that time could better be allocated among session activities. The 30-minute plenary presentations were well received, tackling an appropriate amount of content for the time allotted, with presentations being both digestible and thought provoking. However, attendee feedback indicated that the one-hour panel discussions were longer than needed, and they mentioned that the discussions occasionally dragged and became tangential to relevant (targeted) themes. Workshop participants also requested longer breakout sessions to interact and engage with the PACE project science leads and research community. Attendees also requested a more robust virtual meeting platform, citing poor audio quality and video lag and sync issues with the *Adobe Connect* platform.

The NASA Applications team will continue to engage and interact with applied research, data user and stakeholder communities, soliciting their feedback to inform future mission and application activities to fulfill practical societal needs, enable efficient data-driven decision-making processes, and foster collaborative inter- and transdisciplinary partnerships. User feedback and stakeholder engagement through application workshops, like this one, are essential to realizing and achieving the full potential and utility of NASA's next great investment in Earth Science, the PACE mission.

Conclusion

The 2020 NASA PACE Applications Workshop set critical objectives, all of which were meaningfully addressed through a dynamic program of keynote presentations, moderated panel discussions, and audience-engaging participatory activities throughout the four sessions hosted across two days. As a virtual forum, the workshop achieved an incredible level of global interest and multidisciplinary turnout (350 total participants), with a high level of engagement and interaction among the hosts, presenters, and participants. The workshop initiated an interdisciplinary dialogue focused on the PACE mission and how its anticipated data products will support societal needs, including managing water resources, safeguarding human health, supporting air-quality monitoring, responding to a changing climate, and mitigating natural and anthropogenic disasters. The workshop was a resounding success for the PACE mission and in support of NASA applied-science initiatives.

The 2020 Workshop was the first in a series of anticipated annual PACE Applications events. In the coming months, the PACE Applications team will use feedback obtained during and after the workshop to develop and design future events to build on the success of this first Workshop. Ultimately, these activities will support the integration and adoption of anticipated PACE data into practical applications that benefit society and build active partnerships between data producers and the PACE applications and user communities.

The post-event survey posed a quantitative question to gauge interest in future virtual versus in-person PACE Applications activities. Of the 79 total respondents, 63% indicated that they would attend future virtual or in-person PACE events, while 28% responded that they would attend only if the event was virtual again, and 5% percent indicated that they would only attend an in-person event. This feedback will be taken into consideration as plans are made for the future PACE Application Workshops and other focus sessions, tutorials, and meetings. Stay tuned to the PACE website for news of future meetings. ■

ICESat–2 Mission Update and Virtual 2020 Science Team Meeting Highlights

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Introduction

An Ice, Cloud, and land Elevation Satellite 2 (ICESat-2) Science Team Meeting (STM) was held virtually on September 21–22, 2020. It was the first STM gathering of the newly constituted ICESat-2 Science Team (ST) that was selected in February 2020—see "New ICESat–2 Science Team Selected" on page 28. Given that the meeting was conducted online, there were many changes in how it was managed and the amount of content included, compared with past meetings. On the whole, the attendees would have preferred an in-person meeting, but one advantage was that more people were able to participate than at a usual face-to-face meeting.

This article begins with a brief update on the status of the ICESat-2 mission and its laser altimeter instrument—the Advanced Topographic Laser Altimetry System (ATLAS). It then summarizes the highlights from the STM.

ICESat-2 Mission Update

Launched in 2018, ICESat-2 remains healthy and continues to collect high-quality science data. (As of November 1, 2020, ICESat-2 has collected science data for more than 11,500 orbits.) The orbit of ICESat-2 repeats every 91 days, allowing cyclical elevation-change measurements to be made. As of this writing, ICESat-2 has completed eight full cycles and is partway through its ninth. Researchers have also been using ICESat-2 data to calculate the changing mass of ice sheets in Antarctica and Greenland, and to estimate sea ice thickness in the Arctic Ocean. As reported on in greater detail in this STM summary, the expanded ICESat-2 ST started work this spring to broaden the use of the mission's data.

Land Ice Studies

In the first major study of land ice using ICESat-2 data, scientists generated precise, detailed measurements of how the elevation of the Greenland and Antarctic ice sheets have changed over 16 years, as warming global temperatures lead to increased ice melt in Earth's polar regions. To obtain these results, the researchers used ICESat measurements from 2003–2009 and overlaid the tracks of ICESat-2 measurements from 2019, comparing elevation data from the tens of millions of sites where the two datasets intersect—see **Figure**. This methodology resulted in a determination of the elevation change in the ice sheet. To calculate how much ice has been lost, the researchers developed a new model

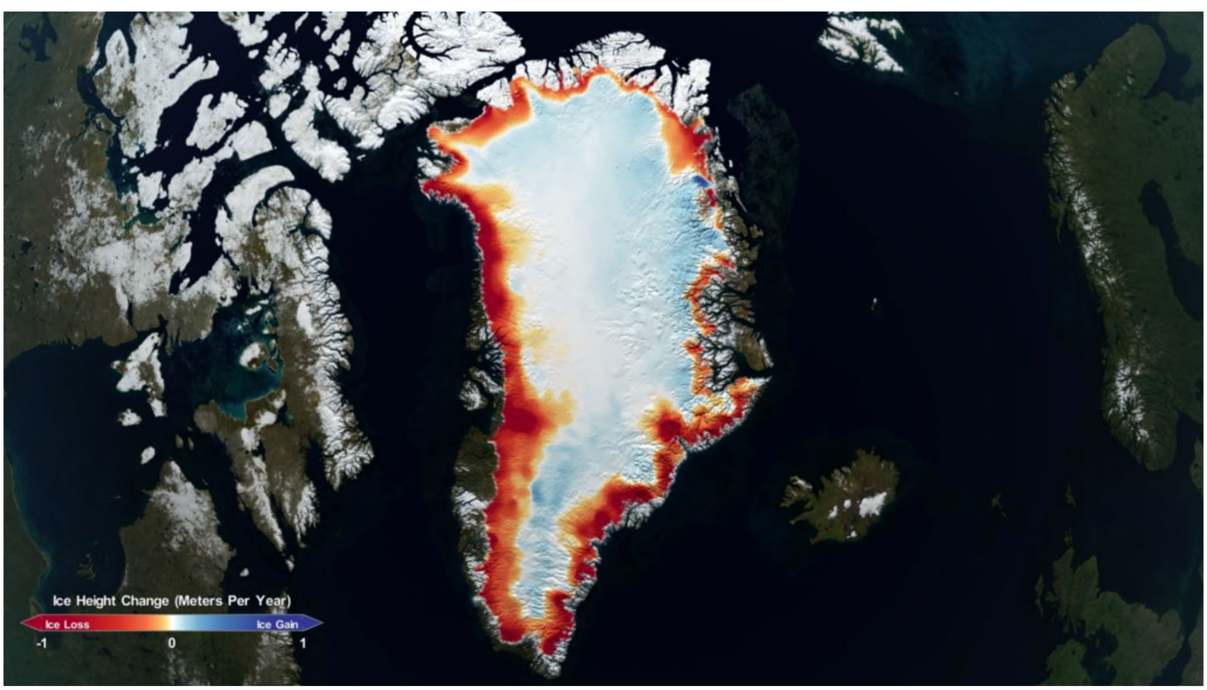


Figure. This data visualization still frame illustrates changes in the thickness of the Greenland Ice Sheet over 16 years, derived by comparing data gathered by the original ICESat from 2003 to 2009 and by ICESat-2 in 2019. The full visualization can be viewed at: *https://svs.gsfc.nasa.gov/13600*
Image credit: NASA's Scientific Visualization Studio

to convert height change to mass change. The model calculated densities across the ice sheets to allow the total mass loss to be calculated.

Sea Ice Studies

Scientists have also been investigating sea ice thickness and the depth of the snow atop the ice. Arctic sea ice (shown in photo on page 29) helps keep Earth cool, as its bright surface reflects the Sun's energy back into space. Each year scientists use multiple satellites and datasets to track the extent of Arctic sea ice, but its thickness is harder to gauge via satellite observations. Initial results from ICESat-2 suggest that the sea ice has thinned by as much as 20% since the end of the first ICESat mission in 2009, contrary to other studies that find sea ice thickness has remained relatively constant in the last decade.

ATLAS Update

ATLAS is taking precise elevation measurements of Earth's surface, with a focus on the polar regions. It was reported at the 2020 ICESat-2 STM (described in more detail later) that ATLAS's health is nominal and for the most part it is performing as expected.

Recently, the ICESat-2 Project Science Office (PSO) has been analyzing the potential impact of the Starlink satellites[1] based on the possible ICESat-2 laser reflections off of their solar panels. The result of the analysis is that it does not pose a grave threat to the ATLAS receiver but could contribute to a decrease in total lifetime for active ATLAS detectors. However, at most, only one such event per year is expected. In addition, the PSO is working with Starlink to assess the potential of the ATLAS laser beams to damage the star trackers of the Starlink satellites as they transit through the ICESat-2 orbit. That analysis continues.

The PSO has also been studying artifacts in the data that are caused by the ATLAS instrument response. The artifacts are noticeable as multiple returns at systematic distances [2.3 m (7.5 ft) and 4.2 m (13.8 ft)] from the primary surface reflection and are attributed to internal reflections within the ATLAS optical components. All of this points to the need for users of data to be aware of nongeophysical returns (e.g., the internal reflections) and to proceed carefully when the returns are saturated.

ICESat-2 Virtual Science Team Meeting Overview

Day one of the two-day STM included comments from **Jack Kaye** [NASA HQ—*Associate Director for Research of the Earth Science Division (ESD)*] and **Thorsten Markus** [NASA HQ—*Cryospheric Sciences Program Manager*] that helped to place ICESat-2 in the broader context on NASA's ESD and ESD's Cryospheric Sciences Program, respectively. The first day also featured updates from ICESat-2 PSO representatives that included reports on data-reprocessing plans, data-validation results to date, and ATLAS operational studies. Day two provided the opportunity for each of the 24 project principal investigators (PIs) from the newly selected ST to give presentations on their current research results and plans for future efforts. Included

[1] Starlink is a satellite constellation of thousands of small satellites being built and launched by SpaceX that will work in combination with ground transceivers to provide internet access. For more information, visit *https://www.starlink.com*.

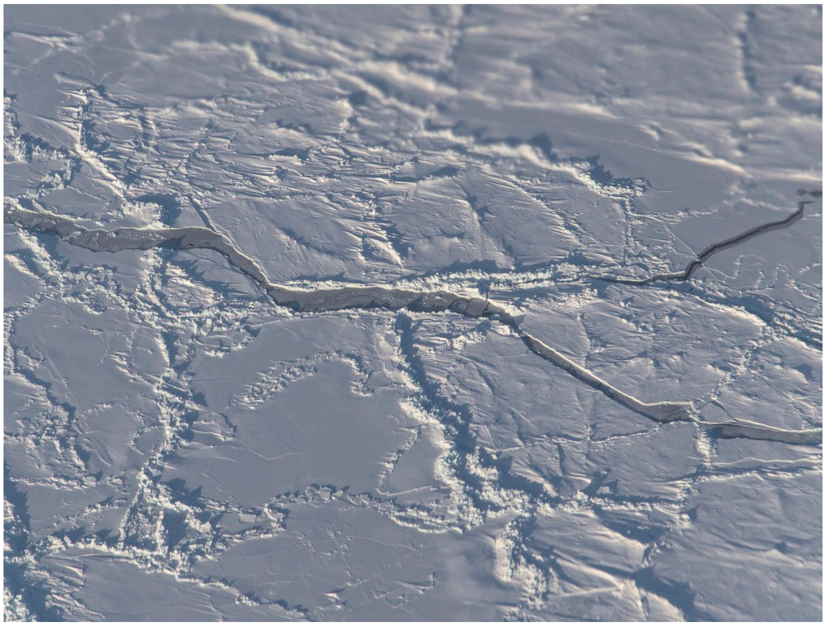
New ICESat-2 Science Team Selected

In February 2020, NASA Headquarters (HQ) announced the selection of the new ICESat-2 Science Team (ST). These selections followed the competitively selected Science Definition Teams in 2011 and 2014. The twelve members of the 2014 Science Definition Team stayed in place through the end of 2019 and saw the mission through the launch and early orbit phases.

The 24 principal investigators and 25 co-investigators on the ST (37 of whom are new to ICESat-2) will be using ICESat-2's height data to answer questions relating to land ice, sea ice, vegetation, water, and the atmosphere, as well as combining those data with data from other instruments. They will be investigating how much ice is lost from ice sheets and glaciers, contributing to sea level rise, as well as cataloging the rifts across the Antarctic ice sheet. They will examine different properties of sea ice, studying the topography of the floes, and measuring the depth of snow on top of the ice.

Beyond the polar regions, the ICESat-2 ST members have projects that are looking at coastal ecosystem structure, tree density in boreal forests, and changes in tropical savannas. Other projects focus on changes in the water level of inland reservoirs, mapping near-shore bathymetry, and even tracking ocean phytoplankton populations.

A new proposal call, which closed on October 30, 2020, will select additional ST members to be added early in 2021. Those interested in learning more about the ICESat-2 ST can download the document at *https://bit.ly/34UNwCx* to read the accepted proposals.



Scientists have used NASA's ICESat-2 to measure the thickness of Arctic sea ice, as well as the depth of snow on the ice. Here, ridges and cracks have formed in sea ice in the Arctic Ocean. **Image credit**: NASA/ Jeremy Harbeck

here are some of the most significant topics of discussion during the STM.

Status of ICESat-2 Data Products

Data products from October 13, 2018, through July 16, 2020, are currently available from the National Snow and Ice Data Center (NSIDC). The next batch of data will arrive at the science computing facility in mid-November 2020, to cover collections through early September 2020. Several data studies have assessed the absolute accuracy of the ICESat-2 elevation data as well as its precision. Since each ICESat-2 data product has its own strengths and weaknesses, the science team has used several data products as part of this evaluation. Below are some of the highlights of these studies (all of the ICESat-2 data products are described at *https://go.nasa.gov/3fBHfj2*.)

- *ATL03 (Global Geolocated Photon Data)*: Heights (on low-slope regions) are currently accurate to better than ~5 cm (~2 in) with better than ~13 cm (~5 in) of surface measurement precision.

- *ATL06 (Land Ice Elevation)*: Heights (on low slope regions) are currently accurate to better than ~3 cm (~1 in) with better than ~9 cm (~3.5 in) of surface measurement precision.

- *ATL07 (Arctic/Antarctic Sea Ice Elevation)*: Remarkably precise height measurements (i.e., height standard deviation) of 1.9 and 1.5 cm (~0.75 and 0.6 in) respectively, have been obtained over two relatively flat stretches (3 to 5 km, or ~2 to 3 mi) of sea ice.

- *ATL08 (Land Water Vegetation Elevation)*: Height measurements over Finland agreed with airborne lidar, with vertical errors less than 75 cm (~29.5 in). A separate study, in comparison to *in situ* reservoir level gauges, measures water level changes with root mean square error of 14.1 cm (~5.5 in).

Data Release 4 Update

The ICESat-2 team is actively working on reprocessing for the production of Release 4 of the data products. Each of the along-track data products has had updates and adjustments made to its algorithm to address issues identified in Release 3. Additionally, Release 4 will be the first to include updates for the precise pointing determination (PPD) and precise orbit determination (POD) solutions since initial prelaunch implementation. PPD includes a newly tuned Extended Kalman Filter for attitude determination and an alternative approach to determining the laser centroid positions within the Laser Reference System that better eliminates the alignment variation due to thermal fluctuations attributed primarily to the onboard heater cycle. This fix should result in less relative beam motion in the data. The POD team will provide updated pointing calibration in Release 4 that eliminates the biases in pitch and roll for geolocation improvements.

Changes in Release 4 that are relevant to ATL03 include:

- Inclusion of the Multi-Error-Removed Improved-Terrain (MERIT) digital elevation model (DEM) replacing the Global Multi-resolution Terrain Elevation Data (GMTED) DEM. These elevations are provided as a reference for an end user and are not used in the ICESat-2 data processing.

- Provision of tide-free geoid and solid Earth tides, with conversions available to allow a user to convert to mean-tide values if desired.

- Provision of the spacecraft roll/pitch/yaw parameters for the product.

Updates from Science Team Members

ST members presented brief summaries of their research plans, progress against those plans, and recent results. Although the virtual platform limited the time each presenter had available, it was still an excellent way for team members to get to know each other and to explore possibilities for future collaborations. It also supported discussion of how to pool resources. Each presenter was also asked to share his or her existing concerns with the mission generally or challenges in specific research pursuits because of lack of resources or information.

There were also multiple comments from ST members on how valuable the data tools have become. Most of them focused on the algorithms created via Hack Week[2] opportunities, but high praise also went to Open Altimetry[3] and the *icepyx* tool[4] demonstrated by the team from the University of Washington.

Summer sea ice validation was a priority mentioned by several ST members, and this also led to a discussion on the availability of low latency data products to provide timely input to the European Space Agency's CryoSat-2/ICESat-2 Resonance Campaign (dubbed Cryo2Ice).[5]

Cloud computing was another topic raised by many of the ST members as an important capability, but it was unclear how best to use it and if it actually could satisfy the needs of ST members. Both the specific Goddard Cloud environment and more-general Amazon Web Services (AWS) were discussed. NSIDC, the ICESat-2 data center, has begun to plan for making ICESat-2 data products available via AWS, which should be online in mid-2021.

Plotting the Way Forward for Future Discussions

In part owing to the virtual format, there were several items that were planned to be covered during the STM that could not be addressed in the time allocated. These will be topics of discussion at upcoming weekly ICESat-2 telecons, which include:

- satellite lifetime/degradation studies and planning;
- pointing control performance for changes in *spot separation*;[6] and
- pointing strategy programmatics for spring/summer 2021 transition.

Conclusion

The ICESat-2 mission is an ongoing success—and in many cases is exceeding expectations, as data quality continues to amaze the team. Management, resources, and organizational support from the PSO is well received and much appreciated. Researchers are putting the data to work answering a range of questions about Earth's interconnected systems. The findings will go beyond the polar regions to examine issues about our planet's forests, coastal ecosystems, and waterways. To date there have been 49 papers using ICESat-2 data published in the peer-reviewed literature (*https://go.nasa.gov/2UVKecz*) with many others currently in review. The next ICESat-2 STM will be in the April–May 2021 time frame. Meanwhile, the team continues to conduct virtual meetings biweekly to stay abreast of developments. ■

[2] Hack Week took place in 2019. It was a gathering of 20 scientists from NASA and a variety of other organizations to confront both the challenge and opportunity presented by the massive amount of data flowing from ICESat-2 in terms of processing, managing, distributing, and analyzing them. To learn more, see *https://go.nasa.gov/3kWH9TT*.

[3] Open Altimetry is a tool for discovery, processing, and visualizing ICESat and ICESat-2 altimetry data (*https://openaltimetry.org*).

[4] *icepyx* is a *Python* tool for working with ICESat-2 data.

[5] Cryo2Ice was a two-week campaign that took place in July 2020, when CryoSat-2 adjusted its orbit by about 900 m (~2950 ft) to allow it to periodically align with ICESat-2 and enable near-simultaneous measurements of the same ice by both missions. Learn more at *https://earth.esa.int/eogateway/missions/cryosat/cryo2ice*.

[6] Spot separation refers to the distance between the six ATLAS laser spots on the ground. The spots are arranged in pairs, with the left and right spot in a pair separated by 90 m (295 ft).

Summary of NASA's Terrestrial Hydrology Program 2020 Snow Virtual Meeting

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Dorothy Hall, NASA's Goddard Space Flight Center/University of Maryland, College Park, dkhall1@umd.edu

Introduction

NASA's Terrestrial Hydrology Program (THP) held a virtual meeting on September 11 and 14, 2020. NASA's Goddard Space Flight Center (GSFC) hosted the meeting, with about 140 people from 59 different institutions attending online. The program included one day on SnowEx planning (see *NASA's SnowEx Campaign*) and results from past and upcoming campaigns, as well as discussions on an upcoming satellite mission, and one day for breakout group discussions on ongoing and critical science needed to support the THP Snow Roadmap (defined later). Results from ongoing research were presented as posters and as four-minute "blizzard talks" on both days to promote awareness and collaboration among participants. The main objectives of this workshop were to:

- share snow campaign and research results;
- discuss ongoing efforts towards advanced snow estimation and a future snow satellite mission;
- solicit feedback on the THP Snow Roadmap and Implementation Plans;
- identify and prioritize remaining knowledge gaps; and
- engage early-career scientists and a wider community in these efforts.

This report will highlight the main discussion and the action items identified during the meeting. The reader may visit *https://go.nasa.gov/37wl2PL* to view the meeting agenda and download the speakers' slides, posters, and recorded blizzard talks.

Background on the Current State of Snow Measurements

Global *snow water equivalent* (SWE) is a critical observation for understanding the role of snow in Earth's water, energy, and carbon cycles.[1] It is also critical for informing water-resource and snow-related hazard applications. While great progress has been made in recent decades to measure snow albedo and snow-covered area from space, the biggest gap in snow remote sensing is the measurement of SWE, and snow depth, which can be used to estimate SWE. Despite decades of research efforts, there are currently no global SWE observations that provide data at the required frequency, resolution, and accuracy to address key science questions. This will require an advanced Earth system framework that incorporates state-of-the-science snow physics into its algorithms and assimilates multiple remotely sensed observations and *in situ* data.

NASA's SnowEx Campaign

The NASA SnowEx campaigns are part of a multi-year, THP-sponsored effort to test and develop remote sensing technologies to monitor snow characteristics—SWE in particular—from space and to identify optimum multisensor synergies and model assimilation for mapping the critical snowpack properties in a future satellite mission. SnowEx aims to quantify and compare capabilities and limitations of traditional and newer snow estimation techniques across a range of environmental conditions, with an emphasis on articulating satellite remote sensing strategies and requirements. SnowEx allows the NASA snow community to refine the capabilities of new aircraft sensors (e.g., test their relative accuracy and global applicability) to determine if a similar instrument would be suitable for space.

The first SnowEx deployment took place in the winter of 2016-17 with a field and aircraft campaign that was designed to evaluate the sensitivity of different snow remote sensing techniques in a variety of forest densities at Grand Mesa, CO—the location of the largest flat-topped mountain in the world. Some results from the 2016-17 campaign were presented during the virtual meeting.

SnowEx 2020 provided an opportunity to evaluate the efficacy of snow measurement and modeling techniques in multiple mountain ranges and temperate forests of the western U.S. The focus was on L-band interferometric synthetic aperture radar (InSAR) and active/passive microwave observations for SWE retrievals and thermal IR observations of snow surface temperature. Future SnowEx efforts will continue testing these SWE retrieval techniques and other snow observations such as albedo in other regions including:

- cold prairies in interior regions of North America;
- boreal forests (taiga) and arctic tundra of North America; and/or
- a maritime snow environment, e.g., the U.S. Pacific Northwest.

[1] To learn more about why snow measurements are important for a variety of applications, download "Got Snow: The Need to Monitor Earth's Snow Resources," at *https://go.nasa.gov/2VFzqzH*.

Decadal Survey Prioritizes Snow Measurements

The National Academies of Sciences, Engineering, and Medicine 2017 Earth Science Decadal Survey (DS)[2] highlights the need for global snow data, stating that understanding changes to Earth's water cycle is one of the next decade's most important science and application priorities. Surface Biology and Geology (SBG)—which includes snow albedo—is one of the five *Designated Observables* (i.e., high-priority observations) the DS identified, with a hyperspectral imaging spectrometer identified as a candidate measurement approach. The DS also recommends SWE and snow depth observations in the list of prioritized Earth System Explorer missions—one of seven measurements vying for three mission slots. Global SWE observations are a key missing piece in the characterization of the water cycle, but crucial knowledge gaps still exist for snow remote sensing. In this decade several potential opportunities for spaceborne snow observations are possible. In addition, several new techniques and advances are being demonstrated with existing satellites that may offer exciting improvements to current capabilities. It is essential to evaluate these concepts and their value for estimating SWE.

[2] National Academies of Sciences, Engineering, and Medicine, 2018, *Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space*, Washington, DC: The National Academies Press is available at *https://doi.org/10.17226/24938*.

THP Snow Roadmap

In light of the DS recommendations, the THP Snow community has undertaken an effort to produce a *THP Snow Roadmap* (see **Figure 1**). The Roadmap outlines key activities, upcoming opportunities, and milestones to advance global snow sensing capabilities over the next decade towards an overall science goal and vision: To understand the time and space variation in the snow's energy and mass balances along with the extensive feedbacks with Earth's climate, water cycle, and carbon cycle. The current draft of the THP Snow Roadmap provides a near-to-medium-term plan, designed to prepare the snow community for these upcoming satellite opportunities, to improve global snow characterization capabilities, and to meet already identified snow data needs.

DAY ONE

The first day consisted of overview presentations of ongoing work, upcoming activities, and potential mission opportunities. In the morning, presentations focused on the THP Snow program and efforts to refine the THP Snow Roadmap, an overview of recent modeling and field campaign efforts, and an update on progress made on the SnowEx Science Plan.

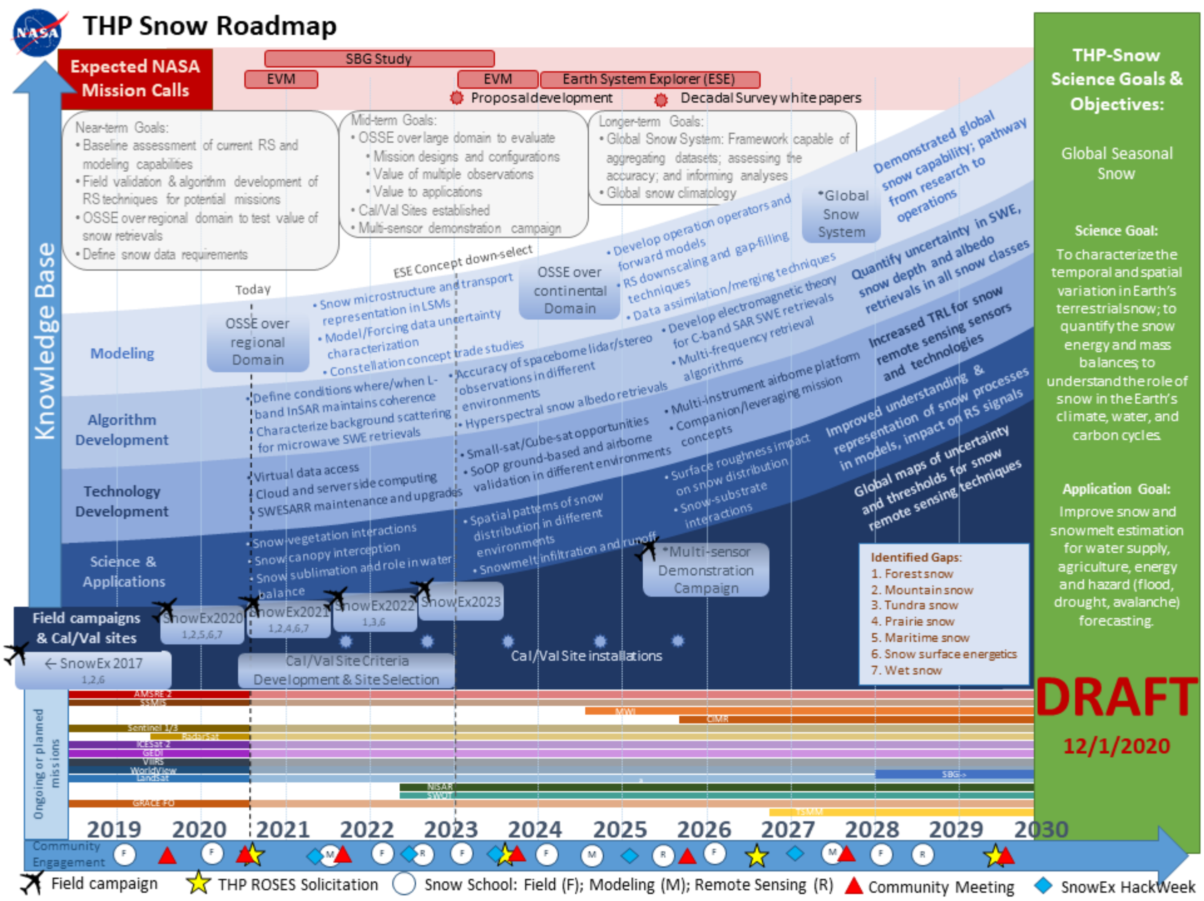

Figure 1. The *THP Snow Roadmap* may be downloaded from *https://go.nasa.gov/2KZjENU*. **Image credit:** Carrie Vuyovich

Dorothy Hall [GSFC/University of Maryland, College Park (UMD), Earth System Science Interdisciplinary Center (ESSIC)—*Snow Program Office Lead*] welcomed attendees and outlined the meeting and the ongoing efforts in NASA's THP Snow program. The 2020 virtual meeting is the third of three consecutive THP Snow meetings that has focused on SnowEx.[3]

Jared Entin [NASA Headquarters (HQ)—*Terrestrial Hydrology Program Manager*] thanked everyone for their many efforts in planning the NASA Snow Program and the 2020 SnowEx campaign. He provided updates on the THP20 Research Opportunities in Space and Earth Sciences for 2020 (ROSES-2020) Solicitation.[4] Entin then switched focus from the specifics of THP to address broader NASA human resources issues. He emphasized that strategies are being developed at all levels within the agency to improve diversity and eliminate bias and harassment at NASA. He further stated that we are all empowered to speak up on these issues, provide feedback, and suggest ways that we can support these ongoing inclusion efforts.

Carrie Vuyovich [GSFC—*THP Snow Project Scientist*] described THP Snow Program future planning and activities, beginning with THP Snow Program goals and the organizational chart. In addition to SBG and Earth System Explorer from the DS, the program targets several potential opportunities for spaceborne snow observations with upcoming missions, which include Earth Venture Missions,[5] the joint NASA-Indian Space Research Organisation (ISRO) Synthetic Aperture Radar (NISAR) mission, and the Canadian Space Agency's Terrestrial Snow Mass Mission (TSMM). Also included are new techniques being developed for, and demonstrated by, existing NASA and international satellites, e.g., NASA's Ice, Cloud, and land Elevation Satellite–2 (ICESat-2) Earth observing altimetry mission, and the European Space Agency's Copernicus Sentinel-1 C-Band SAR mission.

Kelly Gleason [Portland State University] served as moderator for the remaining morning sessions, which focused on progress updates on the SnowEx Science Plan goals, planning for SnowEx campaigns, and modeling efforts. There was also a status update on data archiving at the National Snow and Ice Data Center (NSIDC).

Mike Durand [Ohio State University] talked about the ways in which SnowEx campaigns contribute to snow remote sensing measurement gaps identified in the NASA SnowEx Science Plan.[6] These campaigns are needed to develop the basis for technology selection. While there has been significant progress, there are still critical gaps in our knowledge of SWE sensing techniques, with X-/K_u- band volume scattering, L-band InSAR, lidar, and stereophotogrammetry[7] being the highest priority candidate sensors for development. SnowEx datasets will advance the state of the art in snow measurement techniques to inform technology tradeoff studies for a future DS Explorer proposal. In addition to ground based observations (e.g., SnowEx), modeling and data assimilation are also extremely important elements in NASA's integrated strategy for developing a global snow observation system—see

[3] The first THP Snow meeting took place in Longmont, CO, in 2017; the second took place in Baltimore, MD, in 2019.
[4] See ROSES-2020 Section *A.24—https://go.nasa.gov/3oiGnTA*.
[5] Earth Venture Missions are science-driven, competitively selected, low-cost missions that provide opportunities for investment in innovative Earth science. Venture Class missions are further subdivided into Missions (EVM), Instruments (EVI), and Suborbital (EVS) classifications.

[6] The NASA SnowEx Science Plan can be downloaded from *https://go.nasa.gov/36u3zb3*.
[7] Stereophotogrammetry is a technique to estimate three-dimensional structures from two-dimensional image sequences.

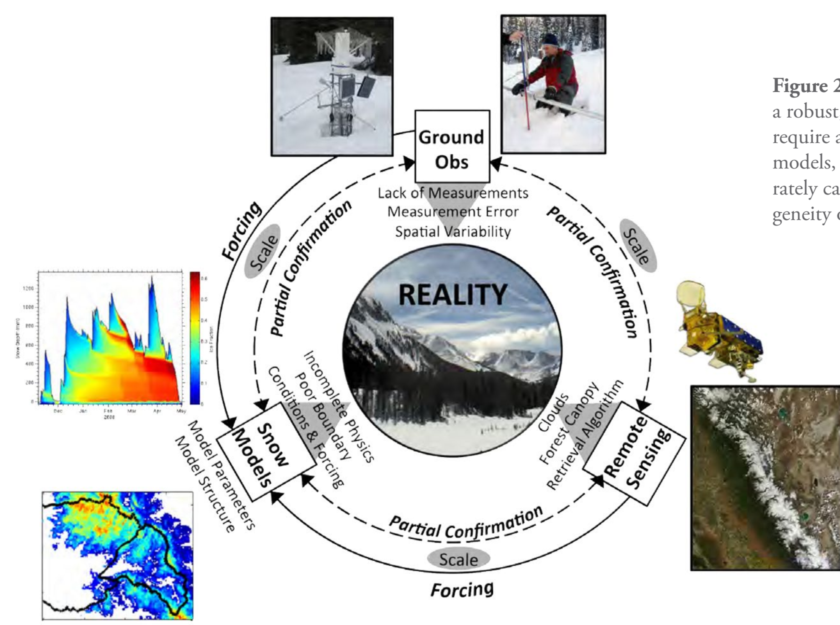

Figure 2. *Integrated Strategies*. Developing a robust, global snow observing system will require a combination of remote sensing, models, and ground observations to accurately capture the spatial and temporal heterogeneity of snow. **Image credit**: Mark Raleigh

Figure 2. Another key component is collaboration with other agencies and other countries. **Melissa Wrzesien** [GSFC/Universities Space Research Association (USRA)] discussed the Snow Ensemble Uncertainty Project (SEUP) and other recent modeling efforts in support of SnowEx. The motivation for SEUP was to estimate spatially distributed SWE and to characterize its measurement uncertainty across North America. Use of ensemble land surface models (LSMs) can provide a baseline estimate of SWE, along with related uncertainty, to inform NASA's Land Information System (LIS) framework. An LSM ensemble with uncertainty can be used in a data assimilation framework. Wrzesien provided details about SEUP Phase 2—an Observing System Simulation Experiment (OSSE) for planning a snow-focused mission. Snow-focused OSSEs are needed to evaluate the impact of proposed missions on improving SWE estimation and its impact on hydrology and climate applications.

Hans Peter "HP" Marshall [Boise State University] described the NASA SnowEx 2020 campaign, which included a *time series campaign*, with weekly-to-biweekly Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) flights over 13 sites in the Western U.S., and an *intensive observing period* (IOP) over Grand Mesa, CO. More than 100 students and researchers from more than 20 organizations participated to obtain snow pit[8] observations (see photo below) and measure snow liquid water content, temperature, density, SWE, depth, and other snow parameters. Lidar and hyperspectral data were also collected over several locations. During the Grand Mesa IOP, several aircraft flights took place to collect a variety of data including backscatter and brightness temperature measurements using GSFC's Snow Water Equivalent Synthetic Aperture Radar and Radiometer (SWESARR) and snow surface temperature and thermal infrared measurements with the University of Washington's airborne Compact Airborne System for Imaging the Environment (CASIE) sensor suite. There were also aircraft flights of the University of Alabama Remote Sensing Center Airborne ultra-wideband, frequency-modulated, continuous-wave (UWB FM-CW) Radar and the National Oceanic and Atmospheric Administration's National Operational Hydrologic Remote Sensing Center (NOHRSC) Gamma Airborne Survey. Marshall concluded his presentation by reviewing the objectives of SnowEx 2021, including a slide showing possible SnowEx 2021 targets and recommendations.

[8] A snow pit is a trench exposing a flat, vertical snow face from the snow surface to the ground, which allows the characteristics of the snow to be studied.

Megan Mason [Boise State University] gave an update on SnowEx data delivery to NSIDC. She discussed data access tools and submission information. She also showed a list of the SnowEx 2017 and 2020 airborne measurements, field measurements, and ground-based instrument datasets provided to NSIDC. Mason then provided a status update on new data releases in 2020 and data from the 2017 and 2020 campaigns that are still being processed for public release.

Do Hyuk "DK" Kang [GSFC/ESSIC] served as moderator for the afternoon presentations, which focused on upcoming opportunities for satellite snow observations.

Ed Kim [GSFC] presented future snow mission opportunities in the context of the 2017 DS. Though some global snow products already exist, a snow mission must provide a quantifiable improvement in global SWE, using multiple remote sensing techniques, leveraging sensors that are already in orbit or planned, along with modeling. All of the tools required to deliver a global SWE data product must be laid out in the proposal, and the key mission sensor should fill remaining gaps. SnowEx and other THP snow activities need to be assessed to identify and prioritize their potential to support the DS Explorer concept. Having summarized what needs to be part of the proposal, Kim ended by proposing a notional timeline of activities that would lead to a snow mission proposal—likely within two years.

Jewell Lund [University of Utah] and **Trey Stafford** [NSIDC] collect snow pit observations during SnowEx 2020 at Grand Mesa, CO. These are combined with snow specific surface area (SSA) measurements obtained by **Celine Vargel** [Université de Sherbrooke, Canada]. **Photo credit:** Megan Mason

Chris Derksen [Environment and Climate Change Canada (ECCC)—*Principal Investigator of the Science Team for the K_u-Band Radar Mission*] discussed the proposed K_u-band radar mission for seasonal snow, which is a partnership between ECCC and the Canadian Space Agency. This mission would acquire 500-m (1640-ft) resolution K_u-band radar measurements to cover Northern Hemisphere snow-covered areas every five to seven days. Current satellite-derived SWE products do not meet ECCC requirements for spatial resolution, accuracy, and latency; therefore, a new space-based approach is necessary. Community-wide collaborations, including NASA, the University of Michigan, and the Finnish Meteorological Institute, have helped support this effort, which has a potential launch date in 2027, followed by a nominal three-year operating phase.

Rick Forster [University of Utah (UoU)] described the NISAR mission and its applications to snow hydrology. NISAR is designed to capture Earth's dynamic surface over time using an L-band InSAR technique. Launch is planned for late 2022. NISAR will provide information on changes in Earth's ice, ecosystems, and biomass, solid Earth deformation and coastal processes, and will enable an assessment of the human impact of changes. Forster presented some details on how L-band InSAR data would support applications in the cryosphere, for global forests and for disaster response. For snow, L-band InSAR provides an estimate of SWE change between observations. Forster also presented recent promising results from SnowEx 2020, which compared SWE retrievals from L-band InSAR to snow depth change observations from lidar over Grand Mesa, CO, and described a ground-based experiment at Bogus Basin, ID, conducted by the U.S. Army's Engineer Research and Development Center (ERDC) Cold Regions Research and Engineering Laboratory (CRREL).

Tom Neumann [GSFC—*ICESat-2 Project Scientist*] provided the workshop attendees an update on ICESat-2 and applications to SnowEx.[9] ICESat-2 has made over one trillion measurements since its September 2018 launch. Neumann reported on the current status, orbit, and coverage of the Advanced Topographic Laser Altimeter System (ATLAS), developed at GSFC. He showed the ICESat-2 coverage over the primary SnowEx field site, Grand Mesa, CO, followed by the relative height of ground tracks over Tuolumne Meadows, CA, from ICESat-2 "snow-off" measurements. Neumann closed with an informative description of the Canopy Height and Glacier Elevation (CHANGE) mission concept, which combines lidar and stereophotogrammetry to measure fine-scale elevation changes in ice and vegetation structures and has potential value for seasonal snow.

[9] To learn more about ICESat-2, see the "ICESat-2 Science Team Meeting Summary" on page 27 of this issue.

McKenzie Skiles [UoU] described NASA's new study for SBG. Snow albedo is a primary control on snowmelt rates, yet current multispectral satellite-borne instruments lack the spatial, spectral, and temporal resolution to measure snow albedo in mountainous terrain with quantitative certainty. Skiles outlined the objectives of the SBG study and provided the current status. Skiles showed the outline of the Pathfinder Study, in which SnowEx data would be valuable in years one through three of operations. Launch is expected no earlier than 2027.

DAY TWO

Day two of the SnowEx Virtual Meeting included dedicated time for group discussions. Breakout sessions were organized by existing Working Groups and tasked with identifying requirements necessary to achieve their science goals and providing feedback on the draft THP Roadmap. Each session was preceded by an overview presentation describing the current Roadmap, the Breakout group charge, and planned discussion topics.

David Shean [University of Washington] moderated the morning session, which focused on current snow science and snow-estimation techniques. **Carrie Vuyovich** presented the THP Snow Roadmap and posed the following questions to the breakout groups:

- *What is the current state of the science?*
- *What are the knowledge gaps that need to be addressed?*
- *What ongoing research contributes to the Roadmap?*

The morning included 30-45 minutes for the breakout sessions, summarized here for each group, followed by a group discussion, with **Manny Salgado** [Texas A&M University] serving as moderator.

Modeling Group

The modeling group, led by **Rhae Sung Kim** and **Melissa Wrzesien** [both from GSFC/USRA], discussed the importance of increased synergy between modeling efforts and field campaigns. Discussion points included how model estimates can be used to inform field campaigns (e.g., observation type, campaign timing, field-site location), what observations would be most useful for improving model representation of important snow processes, and the need for long-term field sites with a full suite of meteorological observations.

Microwave Group

Leung Tsang [University of Michigan] and **DK Kang** led a discussion of an X-/K_u- band volume scattering method for SWE retrieval. The group focused on ways to improve the SWE retrievals, which include incorporating snow physical models and microwave radiative transfer models in retrieval algorithms. The group identified several remaining gaps to address (e.g., the impact of substrate, microstructure, and forests on the signal) as well as possible solutions. A review paper is currently being prepared that describes the technology readiness of microwave radar volume scattering.

Lidar/Stereo Group

Nancy Glenn [Boise State University] and **David Shean** [University of Washington] led this discussion. The Lidar/Stereo working group is a new effort to bring together those interested in advancing the use of lidar, stereo, and the fusion of these technologies for snow studies. The group discussed several areas of potential focus, including assessment of currently available in-orbit satellite data such as spaceborne lidar from ICESat-2 and NASA's Global Ecosystem Dynamics Investigation (GEDI) mission deployed on the International Space Station, and high-resolution stereo imagery available from WorldView,[10] SkySat,[11] and Pleiades.[12] An important outcome of the discussion was identification of the need for more standardization in SfM collection and processing, as well as other Unpiloted Aerial Vehicle data collection.

Albedo Group

Charles Gatebe [GSFC/USRA] and **Anne Nolin** [University of Nevada, Reno] led this discussion of proposed plans for albedo data collection during the SnowEx 2022 campaign in tundra/taiga. Characterizing forest structure and determining the influence of forests on the snowpack energy balance will be important aspects of the campaign, for which the goal is to better understand change in snow albedo over time and space, in the context of scaling and uncertainty considerations. The group discussed potential sites in Alaska, ground and airborne instruments, and time periods for data collection.

L-Band InSAR Group

Elias Deeb [ERDC CRREL] and **Jewell Lund** [UoU] led this discussion, which focused on UAVSAR acquisitions collected during SnowEx 2017 and SnowEx 2020. These data provide a baseline assessment of the L-band InSAR approach toward the estimation of SWE—see **Figure 3**. The group discussed remaining knowledge gaps that need to be addressed with the data, e.g., loss of coherence due to changes in soil conditions, snow wetness or melt–freeze cycles, heavy snow accumulation, extreme differences in snow microstructure, and general radar challenges in steep terrain and vegetation. Other discussion topics included ways that future campaigns could help address these issues.

Science and Applications Group

Ryan Webb [University of New Mexico] and **Kate Hale** [University of Colorado Boulder] led a discussion on the need for global snow data to address various research questions and application needs. SWE data are especially critical for water resource applications and are available in certain areas for various lengths of time, but there are significant gaps in global and temporal coverage. The group identified several operational agencies that would

[10] WorldView is a series of high-resolution Earth observing satellites developed by Digital Globe.
[11] SkySat is a constellation of small satellites operated by Planet, collecting commercial high-resolution Earth imagery.
[12] Pleiades is a constellation of two very-high-resolution optical Earth observing satellites developed by a French–Italian collaboration.

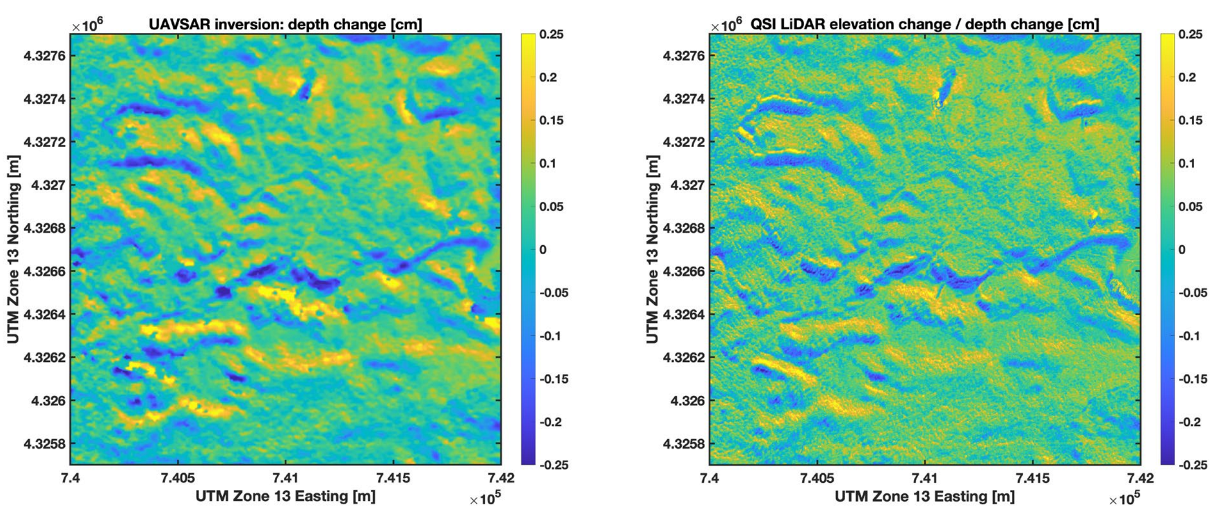

Figure 3. Preliminary results from SnowEx 2020 show good snow depth change agreement between L-band InSAR and lidar data: R-value = 0.76, RMSD=4.7 cm depth, 0.9 cm SWE. Ongoing work will help define limitations in wet snow, vegetation, and steep topography. **Image credit**: HP Marshall

benefit from improved snow data and discussed ways to promote usefulness or access to data, including standard file types, open access tools, broader communication of data availability, and increased collaboration between science and application groups.

Shadi Oveisgharan [NASA/Jet Propulsion Laboratory (JPL)] served as moderator for the afternoon session, which focused on evaluating and developing snow observations with global coverage. **Charles Miller** [JPL] discussed opportunities for a joint SnowEx–ABoVE Campaign that would cover the boreal forest, Bering tundra, North Slope tundra, and the Arctic tundra. He discussed ways to leverage Arctic-Boreal Vulnerability Experiment (ABoVE)[13] infrastructure and logistics and established *snow-off*[14] flight lines. **HP Marshall** discussed the future of planning for global snow measurements, and then posed the following questions to the breakout groups:

- What activities are missing/essential?
- How does the timeline match with upcoming deadlines?
- What partnerships or other opportunities should we be aware of?

The afternoon included 30-45 minutes for the breakout sessions, summarized in the next section, followed by a group discussion, with **Carrie Vuyovich** serving as moderator.

Snow Strategic Planning Group

Paul Houser [George Mason University] and **Ana Barros** [Duke University] led this discussion, which was organized by four questions formulated in the context of the overall science, application, and satellite mission goals presented in the central meeting. The questions were:

- *What are the research, reviews, and answers that must be ready by proposal time?*
- *How do we prioritize research, roadmap tasks, etc.?*
- *How do we focus and motivate the snow community towards a mission?*
- *How do we strategically position our community for success?*

A successful satellite mission proposal will meet science and application targets by implementing a technically feasible measurement strategy under required cost caps. In addition to a high technology readiness level (TRL), success is predicated upon a collaborative interdisciplinary framework and deliberate engagement of international partners.

Prairie Snow Group

Sam Tuttle [Syracuse University] and **Eunsang Cho** [GSFC/ESSIC] provided an overview of the plans for the SnowEx 2021 prairie effort. The main goals for this effort are to assess the spatial distribution of snow properties in a prairie environment, evaluate the impact of shallow snow and soil properties on L-band InSAR, and gain insight into the instrumentation and measurement requirements for long-term remote sensing calibration/validation in the prairie. There was also discussion about the potential for passive microwave measurements in prairie environments; while it shows value, there are still numerous factors that affect the signal that need further exploration.

Tundra/Taiga Snow Group

Mike Durand [Ohio State University] and **Chris Hiemstra** [ERDC CRREL] led this discussion, which focused on the proposed boreal and Arctic SnowEx 2021-2022 Alaska field campaign. There was some conversation about how long lidar datasets are applicable in regions where bare-earth surfaces and vegetation are changing, and the application of SfM in measuring snow depths in forested locations. Much of the discussion centered on spatial scales; multiscale and cross-scale approaches to the questions are crucial considering remote sensing approaches and field measurements in these high-latitude environments. The group also discussed ways that ABoVE datasets and knowledge could be leveraged to understand the scale question.

Maritime Group

Mark Raleigh [Oregon State University] and **Elizabeth Burakowski** [University of New Hampshire] led a discussion on the unique challenges facing snow remote sensing in maritime environments. Big challenges impact snow remote sensing in maritime regions including variable precipitation type, complex terrain combined with dense forest cover, and more-persistent cloud cover. The group discussed the importance of partnerships with the atmospheric science community and modeling efforts to improve snow estimation in these regions. However, snow conditions are heavily influenced by storm patterns and vegetation types in the region and it therefore may be difficult to generalize across different maritime environments.

[13] Learn more about ABoVE at *https://above.nasa.gov*.
[14] *Snow-off* refers to airborne observations collected during snow-free conditions, which can be used as a baseline for comparison to snow-covered observations.

Snow OSSE Group

Barton Forman [UMD] and **Sujay Kumar** [GSFC] led a discussion on the use of OSSEs, which are used to simulate new observing systems for snow. The conversation focused on the key components of the OSSE system, which includes the orbital simulator (space–time subsampler), observation simulator, observation operator, land-surface models, end-use applications, and evaluation metrics. There is a significant need to specify the spatiotemporal scales of the anticipated instruments and the expected error levels from these sensors. A critical gap in the OSSE environment is the ability to work with the raw satellite measurements, which requires appropriate radiative transfer models, though there are additional uncertainties associated with this. Given the large suite of instruments and technologies being considered within the THP Snow community, the use of machine-learning methods to understand the sensitivities of retrieval methods should also be a priority.

Blizzard Talks

On both days, participants heard a series of four-minute Blizzard Talks and/or posters. **Dan McGrath** [Colorado State University] and **Jessica Lundquist** [University of Washington] moderated these short presentations, which were given to provide an overview of recent research results and foster discussion and collaboration among members of the Snow community. These presentations focused primarily on research using data collected during the SnowEx 2017 and 2020 campaigns, recent modeling efforts, and related snow research efforts. The recorded blizzard talks and posters can be found on the meeting website at *https://go.nasa.gov/37wl2PL*.

Overall Meeting Outcomes and Next Steps

The SnowEx Virtual Meeting highlighted a number of opportunities that will arise over the next decade to advance snow remote sensing and science, such as planned or potential satellite missions, modeling studies, and field campaigns. Activities needed to prepare for these opportunities and to make progress towards overall snow science goals are outlined in the THP Snow Roadmap and were discussed during the meeting. Attendees are encouraged to provide any additional feedback they think would further improve these efforts.

A recurring focus of discussion was identifying opportunities for participation, especially for early-career and underrepresented groups, and improving diversity, equity, and inclusion. Ideas for increasing such participation include the snow field, modeling and remote sensing schools, SnowEx Hack week[15] (both participating in it and helping to develop scripts and tutorials) joining various THP Snow working groups, and helping develop content and input to the *snow.nasa.gov* website.

A missing component of the proposed activities is a comprehensive plan for addressing spatial scaling. This needs to be considered prior to field campaign planning and should include people across different working groups in developing this plan. Work to evaluate spatial patterning has shown promise and should also be considered, with deliberate plans on how to test it in respective domains for future campaigns. A meeting will be scheduled for the near future to discuss this further.

The SnowEx Virtual Meeting showcased the ongoing, wide-ranging, and innovative snow research in NASA's Terrestrial Hydrology Program. There is a high level of engagement and excitement across the Terrestrial Hydrology Program snow community as we work toward the common goal of improving the estimation of global SWE and other snow properties using satellite remote sensing along with modeling and field measurements. The Terrestrial Hydrology Program at NASA has supported research that has led to breakthroughs in our understanding of snow processes that will be instrumental in the development of a future snow mission. ■

[15] SnowEx Hack week is a workshop, currently scheduled for summer 2021, to provide training, foster collaboration and community-building, and promote interest in the SnowEx data using open-source scientific workflows. A similar event was held for ICESat-2 in 2019. See "ICESat-2 Science Team Summary" on page 30 of this issue to learn more.

Summary of the Sixth DSCOVR EPIC and NISTAR Science Team Meeting

Alexander Marshak, NASA's Goddard Space Flight Center, alexander.marshak-1@nasa.gov

Introduction

The sixth Deep Space Climate Observatory (DSCOVR) EPIC and NISTAR[1] Science Team Meeting (STM) was held virtually on October 6-8, 2020, and was attended by over 60 people. While most participants were from NASA's Goddard Space Flight Center (GSFC), there were also attendees from NASA's Langley Research Center (LaRC), NASA/Jet Propulsion Laboratory (JPL), Department of Energy laboratories, and several U.S. universities. There were also several European participants from Finland, Estonia, Germany, and Spain.

A full overview of DSCOVR was given in the summary of the 2018 DSCOVR STM and will not be repeated here.[2] This article presents the highlights of the 2020 meeting; the full presentations can be downloaded from *https://go.nasa.gov/3fLJ2lH*.

Opening Presentations

The opening session consisted of a series of presentations from DSCOVR mission leaders and representatives from GSFC and NASA Headquarters (HQ), who gave updates on the mission and its two Earth science instruments. Presenters discussed DSCOVR's extended stay in safe mode from June 27, 2019, to February 11, 2020, and the NASA Earth Science Division (ESD) 2020 Senior Review[3] report (which was presented to NASA HQ on July 10, 2020).

Alexander Marshak [GSFC—*DSCOVR Deputy Project Scientist*] opened the meeting. He discussed the agenda for the meeting—the first-ever held virtually (due to the ongoing COVID-19 pandemic)—and mentioned that the mission successfully passed the 2020 Earth Science Senior Review. The review recommended that EPIC and NISTAR continue to receive funding through Fiscal Year 2026 for operations and data analysis.

Adam Szabo [GSFC—*DSCOVR Project Scientist*] provided an update to attendees on the status of DSCOVR, stating that the mission returned to full operational service on March 2, 2020, after a nine-month hiatus due to the deterioration of its gyros. He explained that the spacecraft—now relying only on its star tracker for attitude determination—is able to return Earth images at the same rate as before the event. Moreover, recent flight software updates eliminated the spurious safe holds experienced by the spacecraft during its first few years of operations. DSCOVR has ample fuel and power generation capabilities to continue operating for at least through 2030—and probably longer. The ESD Senior Review panel agreed with this assessment and recommended continuing the mission for the next three years.

Steve Platnick [*GSFC—Deputy Director for Atmospheres in the Earth Sciences Division*] welcomed meeting participants to the virtual meeting on behalf of GSFC's ESD. Platnick noted his appreciation for all mission team members who have worked hard to maintain operation of the DSCOVR satellite and instruments during this challenging time and, in particular, for those who contributed to the successful return to operations earlier this past March. Platnick commended Szabo and Marshak for leading the effort to assemble the superb 2020 Senior Review proposal to extend operations and data production for the EPIC and NISTAR instruments. He thanked NASA HQ for its continued strong support for the mission.

Richard Eckman [*NASA HQ—DSCOVR EPIC/NISTAR Program Scientist*] welcomed the members of the DSCOVR Science Team and all friends of EPIC and NISTAR observations. He noted that a new call for proposals will be included in ROSES-2021.[4] He looked forward to learning about recent accomplishments by Science Team members, which will be essential in assessing the mission's performance.

Updates on Science Operations, Data Products, and Processing

The DSCOVR mission components continue to function nominally, with progress being reported on several fronts, including data acquisition, processing, archiving, and release of new versions of several data products. The number of users is increasing, with a new Science Outreach Team having been put in place to aid users in several aspects of data discovery, access, and user friendliness. See **Table 1** on the next page for a summary of the discussions.

[1] The two Earth-viewing instruments onboard DSCOVR are the Earth Polychromatic Imaging Camera (EPIC) and the National Institute of Standards and Technology (NIST) Advanced Radiometer (NISTAR).

[2] See "Summary of DSCOVR EPIC and NISTAR Science Team Meeting" in the November-December 2018 issue of *The Earth Observer* [**Volume 30, Issue 6,** pp. 16-22—*https://go.nasa.gov/37c0M5s*].

[3] Periodically, NASA HQ conducts a review of a subset of its Earth Science missions to assess overall progress toward achieving mission objectives and viability for continuation or extension of the mission.

[4] ROSES stands for Research Opportunities in Space and Earth Sciences. As of this date, the 2021 solicitation had not yet been released.

Table 1. Updates on DSCOVR science operations, data products, and processing.

Presenter [Affiliation]	Topic/Title	Summary Findings
Carl Hostetter [GSFC]	DSCOVR Science Operations Center (DSOC) Level-0 (L0) to L1A/B	Described end-to-end system data acquisition and processing flow; reported status of EPIC Version 3 (V3) and NISTAR V3 reprocessing.
Alexander Cede and **Gavin McCauley** [both from SciGlob]	EPIC L1A Status	Discussed the initial calibration and calibration changes. The observed instrumental changes between October 2019 and October 2020 are small and therefore do not require a reprocessing of the data with updated calibration information.
Marshall Sutton [GSFC]	EPIC L2 Processing	Discussed generating and archiving EPIC L2 science products for all seven EPIC science teams.
Karin Blank [GSFC]	Geolocation Status and the Color Processing Algorithm	Presented the current status of EPIC geolocation (an accuracy anomaly has been resolved) and information on the updated color processing algorithm to address atmospheric scattering, with results that will benefit EPIC and instruments on other spacecraft, as well.
Sanjana Paul and **Danielle Groenen** [both from NASA's Langley Research Center (LaRC)]	Atmospheric Science Data Center (ASDC) DSCOVR Update	Presented DSCOVR L1 and L2 metrics from September 1, 2019, through August 31, 2020. Showed new visualizations of each data version.
Matthew Kowalewski [GSFC]	DSCOVR L1A Calibration Update	Summarized in-flight Earth observations and calibration measurements and instrument's nominal health and performance.

EPIC Calibration

Scientific results from EPIC data have been substantially improved as a result of a release of Version 3 of the Level-1 data, which has much better geolocation. Calibration activities, which covered flat-field calibration, led to ozone retrieval improvements, improved channel calibration coefficients, and the use of lunar observations for calibration trending.

Liang-Kang Huang [GSFC/Science Systems and Applications, Inc. (SSAI)] presented an update on efforts to calibrate the EPIC ultraviolet (UV) channels. Lunar data were analyzed to map changes in EPIC sensitivity as a function of radial distance from the center of the charge coupled device (CCD) that is the detector of the instrument. As a result, a 3.5% drop in the UV channels was used as part of the flat field correction. The comparison of albedos derived from data obtained by the UV channels on EPIC and those obtained from the Ozone Mapping Profile Suite's (OMPS) Nadir Mapper on the Suomi National Polar-orbiting Partnership (NPP) platform has been updated up to August 2020.

Igor Geogdzhayev [Columbia University] presented an update on calibration efforts for the EPIC visible and near-infrared (NIR) channels. He reported on a unified approach to calibrate EPIC visible and NIR channels by comparison with low-Earth-orbit (LEO) radiometers. This approach has been applied to data from the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the Aqua and Terra satellites, the Multiangle Imaging Spectroradiometer (MISR) on Terra, and the Visible Infrared Imaging Radiometer Suite (VIIRS) on the Suomi NPP platform. No significant changes in calibration were detected after the resumption of operations in March 2020. Trends and sources of variability due to viewing geometry differences were reported.

Matthew Kowalewski [GSFC] discussed calibration of the EPIC oxygen (O_2) absorption bands, which use quarterly lunar observations. These lunar observations were used to transfer the absolute radiometric calibration from the nonabsorbing Oxygen A- and B-band wavelengths to the absorbing wavelengths utilizing the independently measured lunar reflectances from the Robotic Lunar Observatory (ROLO). Average lunar signal ratios of the nonabsorbing to absorbing wavelengths continue to demonstrate the stability of the relative radiometric calibration in these channels to within 0.2% with no noticeable trend.

Conor Haney [NASA's LaRC] discussed inter-calibration of the EPIC visible channels using analogous MODIS/Aqua, VIIRS/Suomi NPP, and VIIRS/NOAA 20. The calibration is based on all-sky tropical ocean and deep convective cloud coincident and ray-matched targets. The results show that the EPIC image navigation accuracy was greatly improved between Version 2 and Version 3 of the EPIC data. Haney concluded that both ray-matched EPIC channel gains were mostly within 0.3% of each other, and that EPIC channel radiances obtained since the beginning of 2020 are consistent with those observed before 2020.

Status of NISTAR

NISTAR remains fully functional. With regard to data collected before June 2019, there are some disagreements between data obtained by NISTAR and those obtained by the Clouds and the Earth's Radiant Energy System (CERES) data on both Aqua and Terra. The presentations in this session explored possible explanations for such discrepancies. They also include more details on specific topics related to NISTAR.

Allan Smith [L-1 Standards and Technology, Inc.] explained that the NISTAR Level-1B data products have been updated. Specifically, Release 3.0 includes an optimized noise-reduction filter for the shortwave (SW) channel, and interpolation algorithms have been added to minimize the impact of small data gaps. In-orbit data have shown the SW channel to have a stable gain and offset; however, low-uncertainty measurement of the SW offset remains challenging. Investigation into these issues continues.

Wenying Su [LaRC] described broadband SW radiances derived from the spectral observations of EPIC's 443-, 551-, and 680-nm channels using predetermined narrowband-to-broadband regression coefficients developed from collocated CERES and MODIS observations. She explained that the pixel-level EPIC SW radiances are averaged to provide the global daytime mean radiances, which are then converted to SW fluxes by accounting for the anisotropic characteristic of the radiance field. The EPIC-based global daytime mean shortwave fluxes agree with those from CERES to within 1-2%.

Clark Weaver [University of Maryland, College Park (UMD)] discussed construction of a SW broadband radiance that combines information from the four visible EPIC channels and high-spectral-resolution data from the SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY (SCIAMACHY)[5] observations. Radiances have been computed for two different scene types: cloud-free ocean and thick clouds over ocean. Weaver said that a scatter plot of this EPIC–SCIAMACHY product versus CERES SW radiances (in the direction of DSCOVR) is almost colinear—but not quite.

Andrew Lacis [NASA's Goddard Institute for Space Studies (GISS)] said that EPIC and NISTAR measurements provide precise longitudinal slicing of climate-relevant data with well-defined space–time averaging over the sunlit hemisphere. These results can be accurately aligned with global climate model output data, thus establishing a new and unique diagnostic capability for assessing global climate model performance. Lacis explained that longitudinal slicing comparisons of the GISS ModelE2[6] output data and of the EPIC-derived planetary albedo and cloud-cover fraction integrated over the sunlit hemisphere show excessive cloudiness in global climate model simulations over the oceans and deficient cloud cover over the continents, but with a relative similarity in the seasonal geographical cloud-cover distribution during the summer months.

Daniel Feldman [Lawrence Berkeley National Laboratory] presented results from the DSCOVR platform, using the EPIC and NISTAR instruments to characterize the diurnal cycle of Reflected Shortwave Radiation (RSR). These observations validate the use of geostationary satellites to fill gaps in CERES observations and to show many distinctive modes of variability. He explained that these modes of variability reveal how clouds modulate contributions of RSR from surface albedo at subdiurnal-to-seasonal time scales. They also reveal that most Earth System Models, although tuned to achieve long-term values of RSR that agree with observations, do so incorrectly in that they overestimate the variability and impact of cloud systems in RSR at subseasonal time scales.

Status of EPIC Level-2 Data Products

The presenters during this session gave updates on the status of and/or science results obtained using the various EPIC L2 data products. Most of these products released to the public through LaRC's Atmospheric Science Data Center (ASDC) between November 2017 and June 2018 and were reported on in the 2018 DSCOVR STM Summary referenced in footnote 2. This time presenters reported on Version 2 (or even Version 3) L2 products released to the public. **Table 2** on page 42 summarizes the session. For more details, refer to the original presentations via the URL provided in the Introduction.

[5] SCIAMACHY flew on the European Space Agency's Envisat mission from 2002 to 2012.

[6] For more information on this model, visit *https://go.nasa.gov/2JcenBA*.

Table 2. Status of EPIC data products.

Presenter [Affiliation]	EPIC Data Product(s)	Summary Findings
Natalya Kramarova [GSFC]	Total Ozone (O_3)	Reprocessing the total EPIC ozone dataset using the new Version 3 (V3) ozone algorithm and comparisons with overlapping satellite instruments (Suomi NPP OMPS and Aura Ozone Monitoring Instrument) demonstrated a good agreement.
Kai Yang [UMD]	Total O_3, Volcanic Sulfur Dioxide (SO_2), and Aerosol Index (AI)	The EPIC O_3SO_2AI product provides global total ozone measurements and sulfur dioxide (SO_2) retrievals from volcanic eruptions. Validation shows high accuracies for the total O_3 columns, and algorithm improvements enhance SO_2 estimation accuracy for fresh volcanic clouds through simultaneous retrievals of volcanic ash amounts.
Simon Carn [Michigan Technological University]	Volcanic SO_2	EPIC measurements of SO_2 emissions from small volcanic eruptions show no significant change to data quality since March 2020. Comparisons of hourly EPIC SO_2, UV Aerosol Index (UVAI), and O_2 A-band cloud height data, with IR SO_2 retrievals from the geostationary Japanese Himawari-8 satellite during a major eruption in June 2019, show that rapidly changing optical depth of fresh volcanic eruption clouds impacts the measured SO_2 mass loading.
Omar Torres [GSFC]	Near-UV Aerosol Optical Depth (AOD) and Single Scattering Albedo (SSA)	EPIC UV AI and AOD observations of the 2020 Western U.S. wildfires document the rapid temporal and spatial spread of the smoke plume to cover the entire continental U.S., southern Canada, and northern Mexico, eventually reaching the north and tropical Pacific Ocean and across the Atlantic Ocean and on to northern Europe.
Alexei Lyapustin [GSFC]	Atmospheric Correction	Version 2 (V2) of the EPIC Multiangle Implementation of Atmospheric Correction (MAIAC) atmospheric correction algorithm has been validated with Aerosol Robotic Network (AERONET) sunphotometer data. V2 significantly improved AOD accuracy over V1; retrieved single-scattering albedo in blue wavelengths shows accuracy comparable to that of AERONET for both biomass burning smoke and mineral dust aerosols.
Yuekui Yang [GSFC]	Cloud Products	EPIC L2 cloud products are being upgraded from V2 to V3, which will include new cloud detection algorithms over ice, snow, and sunglint areas, significantly improving the EPIC cloud mask.
Yaping Zhou [Universities Space Research Association]	Cloud Detection over Snow and Ice	A novel cloud detection algorithm for use over snow- and ice-covered regions uses processing differences depending on whether frozen land or ocean surface is being observed. The new ocean cloud mask algorithm improves the diurnal cycles of cloud fraction over ocean.
Robert Frouin [University of California, San Diego]	Ocean Biology/ Biogeochemistry Products	Daily and monthly photosynthetically available radiation (PAR) products derived using new methodology to estimate daily mean PAR and UV fluxes at the ocean surface from EPIC hourly observations agree well with MODIS products—with some improvements.
Yuri Knyazikhin [Boston University]	Vegetation Products	Five parameters have been developed and added to the V2 Vegetation Earth System Data Record (VESDR) parameter suite, V2 has been evaluated on a limited set of data over South America, showing agreement with theory. Reprocessing will be done once V2 of the EPIC L2 MAIAC product (which is input to the VESDR algorithm) becomes available.

Science from DSCOVR/EPIC Data

As is evident from the summaries that appear in this section, EPIC and NISTAR have been used for a wide range of Earth science investigations. To read more about these topics, see the full presentations at the website provided in the Introduction.

Ranga Myneni [Boston University] discussed signatures of vegetation hot spots from synergy between EPIC measurements and those obtained by MODIS, VIIRS, and other sensors to monitor changes in global forests. The talk consisted of two parts: understanding seasonal and long-term changes and their causes in leaf area of Congolian rainforests, and modeling of angular signatures of tropical rainforest reflectances with the goal of attributing changes in these signatures to canopy structure and optics.

Alex Kostinski [Michigan Technological University] reported on preferred spots on the globe where EPIC observes specular sun glint. While monitoring reflectance at these spots, occasional intense glints originating from neither ocean surface nor cloud ice have been observed. Kostinski discovered that mountain lakes high in the Andes are among the causes. Time-averaged reflectance at these spots was also examined and found to exceed that of neighboring locations, with the excess increasing monotonically with separation distance. This specular excess is found in all channels and is more pronounced in the latest and best-calibrated version of EPIC data, thus opening the possibility of testing geometric calibration by monitoring distant glitter.

Tamás Várnai [University of Maryland, Baltimore County (UMBC), Joint Center for Earth Systems Technology (JCET)] reported on deep-space observations of sunglints, presenting an analysis of sunglints caused by horizontally oriented crystals suspended in ice clouds. Statistical analysis of all EPIC images taken in 2017 showed that the wavelength dependence of glints is shaped mostly by atmospheric gases that scatter and absorb sunlight above the cloud top. The analysis also revealed that glints display seasonal variations that are consistent with seasonal changes in the amount and temperature of ice clouds observed by MODIS on both Aqua and Terra.

Alfonso Delgado Bonal [Universities Space Research Association (USRA)] discussed daily variability of cloud amount from EPIC observations. He stated that the unique vantage point of EPIC provides a unique opportunity to study the global daytime variability of clouds using a single sensor. He demonstrated that liquid clouds have opposite daytime evolution between land and ocean, reaching a maximum and minimum around noon, respectively. To the contrary, daytime evolution of ice clouds is independent of the type of underlying surface, with higher values in the morning and afternoon and minimum around noon.

Guoyong Wen [USRA] analyzed three EPIC images during an annular solar eclipse on June 21, 2020, when centers of the eclipse were over the Arabian Peninsula (mostly desert), the Himalayas (mostly barren land), and China (mostly cloud over vegetation). He compared them with two images for selected locations from the 2017 "Great American" total solar eclipse: over Casper, WY, and Columbia, MO (both locations have vegetated surfaces). Global average reductions of spectral reflectance for the three images during the 2020 solar eclipse are quite different, while the reductions of spectral reflectance for the two images for the 2017 solar eclipse are similar. Radiative transfer model simulations suggest that spectral albedo accounts for the difference in these results. The three areas that were imaged during the 2020 annular eclipse have different spectral albedos, whereas the two areas imaged during the 2017 total eclipse have similar spectral albedos.

Jun Wang [University of Iowa] showed that seasonal and diurnal changes of dust-layer height can be revealed by EPIC using its O_2 A-band. The retrieval algorithm was applied for the whole EPIC data record; it showed that the climatology of dust aerosol layer height at local noon, as characterized by EPIC, is generally consistent with that found in the Level-3 data from the Cloud–Aerosol Lidar with Orthogonal Projection (CALIOP) on NASA's Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO). While not able to provide detailed layer information of dust vertical distribution, the layer height retrieved from EPIC O_2A provides unique information to describe diurnal and vertical distribution of the dust due to its large spatial and temporal coverage.

Nick Gorkavyi [SSAI] compared Earth observations from the lunar surface with those obtained by EPIC. The unique view from the first Lagrange point (L1) restricts the phase angles to between 2 and 12°—a nearly backscattering direction. Gorkavyi explained that an autonomic EPIC-like camera on the Moon's surface would offer a unique opportunity to overcome these limitations as it would observe the Earth's disk with phase angles from 0 to 180°. He reported on the concept of operations for a lunar observatory and showed images of Earth from the Moon for half a lunar month.

Jerald Ziemke [Goddard Earth Sciences Technology and Research (GESTAR)] discussed tropospheric ozone derived from EPIC using a new Version 3 retrieval. He showed that it is a very versatile dataset for studying hourly-to-interannual timescale variations. The unique hourly measurements from EPIC are capable of tracking short timescale features such as hour-to-hour changes in tropospheric ozone due to moving weather systems. Ziemke stated that the hourly measurements also provide a useful benchmark for evaluating and testing current and upcoming geostationary measurements of tropospheric ozone such as from the Geostationary Environment Monitoring Spectrometer (GEMS),[7] Tropospheric Emissions: Monitoring of Pollution (TEMPO),[8] and Sentinel-4.[9]

Victor Molina Garcia [German Aerospace Center] showed the latest developments of his model [called the Optical Cloud Recognition Algorithm (OCRA) and Retrieval of Cloud Information using Neural Networks (ROCINN)] to retrieve cloud properties from EPIC measurements. The improvements in OCRA, used to estimate the cloud fraction, include finer temporal resolution for cloud-free maps and analysis of viewing-angle dependencies. Daily cloud-fraction products from MODIS and EPIC-OCRA have been compared and show good agreement for scenes with clear-sky conditions or with optically thick clouds. Some technical aspects of training neural networks as approximators of radiative transfer models, as in ROCINN, were also discussed.

Finally, **Jay Herman** [JCET] described a study—using data from OMI—to examine the effect of latitude, season, and time of day on the 90% inactivation time of COVID-19 (T90). The particular coronavirus responsible for COVID-19 is more susceptible to inactivation by UV-B in sunlight near 305 nm than other strains of coronavirus. A midday exposure at low-to-midlatitudes of about 10-20 minutes is sufficient to cause T90 on surfaces exposed to sunlight.

[7] GEMS flies on the Korea Aerospace Research Institute's GEO-KOMPSAT-2B satellite, which was launched successfully on February 18, 2020. GEMS is the Asian element of a global air-quality-monitoring constellation of geostationary satellites that includes the TEMPO spectrometer.

[8] TEMPO is the first funded project of NASA's Earth Venture Instrument program, which includes small, targeted science investigations designed to complement NASA's larger research missions. It is part of the agency's Earth System Science Pathfinder program. To learn more, see "NASA Ups The TEMPO on Monitoring Air Pollution" in the March–April 2013 issue of *The Earth Observer* [**Volume 25**, **Issue 2**, pp. 10–15, 35—*https://go.nasa.gov/33fmjck*]. The International air-quality constellation (TEMPO, GEMS, Sentinel-4) is discussed on pp. 14–15.

[9] Sentinel-4 is a satellite mission making up a part of the European Copernicus Programme.

Conclusion

At the end of the meeting **Alexander Marshak** mentioned that the Senior Review panel suggested that the DSCOVR mission enhance efforts to engage the broader scientific community by increasing the use of DSCOVR data and demonstrating its scientific value. The participants discussed how to do this more efficiently. One suggestion was to increase content to the EPIC website: e.g., adding new L2 products such as ocean photosynthetically active radiation and aerosol height, daily fluctuation of different products, and the possibility of designing and making gridded L3 products available to the scientific community. Finally, a special issue of the journal *Frontiers in Remote Sensing*, titled "DSCOVR EPIC/NISTAR: Five Years of Observing Earth from the L-1 Lagrange Point," is in the works, with a submission deadline of April 28, 2021.

Overall, the meeting was very successful and provided an opportunity to learn the status of EPIC and NISTAR, the status of recently released improved L2 data products, and the science results being achieved from the L1 point. The next STM will be held in the fall of 2021 (hopefully, in person). Up until now, participation in DSCOVR STMs has been by invitation only. However, next year's meeting will be open to the public. There are an increasing number of users of DSCOVR data worldwide, and the plan is for the agenda to include an opportunity to hear from some of these users, as well as from the ST members. Be sure to check the DSCOVR website periodically for the latest updates from the mission—including details on the next STM, once they are determined. ■

Beating Back the Tides

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EDITOR'S NOTE: This article is taken from *nasa.gov*. While this material contains essentially the same content as the original release, it has been rearranged and wordsmithed for the context of *The Earth Observer*.

It was a sight you don't normally see: a jellyfish lying dead in the middle of a parking lot partly submerged in water. But this was no ordinary parking lot. This particular section of asphalt in downtown Annapolis, MD, is among a growing number of areas prone to frequent flooding in the seaside town—see **Photo 1**. The jellyfish had slipped in from the Chesapeake Bay through an opening in the seawall.

Photo 1. A child plays in high-tide floodwaters in downtown Annapolis, MD on April 4, 2017. **Photo credit:** City of Annapolis

"You can literally kayak from the bay right into this parking lot," said oceanographer **William Sweet** [National Oceanic and Atmospheric Administration (NOAA)] on the September 2020 day that we visited. The tide was relatively low that day.

On days with the highest tides of the year, whole parking lots and streets in Annapolis are underwater, causing delays and traffic congestion. Compromise Street, a major road into town, is often forced to shut down, slowing response times for firefighters and other first responders. Local businesses have lost as much as $172,000 a year—or 1.4% of their annual revenue—due to high-tide floods, according to a study published in 2019 in the journal *Science Advances*.

High-tide floods, also known as nuisance floods, sunny-day floods, and recurrent tidal floods, occur "when tides reach anywhere from 1.75 to 2 ft (~0.5 to 0.6 m) above the daily average high tide and start spilling onto streets or bubbling up from storm drains," according to an annual report on the subject by NOAA. These floods are usually not related to storms; they typically occur during high tides, and they impact people's lives. Because of rising seas driven by climate change, the frequency of this kind of flood has dramatically increased in recent years.

Between 2000 and 2015, high-tide flooding in the U.S. doubled from an average of three days per year to six along the Northeast Atlantic, according to a 2018 NOAA report—see **Figure**. It is especially common along the East Coast and Gulf Coast, where the frequency is up by roughly 200% over the last two decades. In some areas, like Annapolis, MD, the numbers are even more extreme. Annapolis had a record 18 days of high-tide flooding from May 2019 to April 2020, according to flooding thresholds for the city established by NOAA. That's up from the previous record of 12 days in 2018. Before 2015, the record number of high-tide flood days in one year was seven, and the yearly average of high-tide floods from 1995 to 2005 was two.

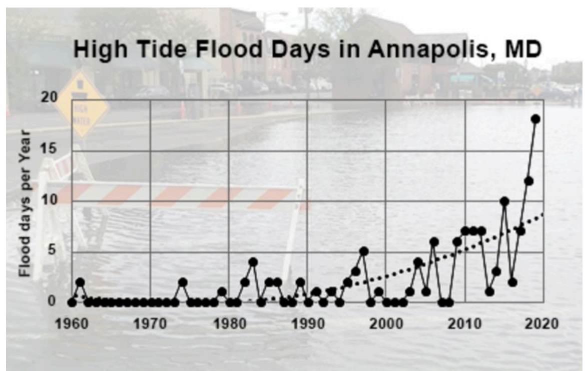

Figure. This plot shows the trend of high-tide flooding days in Annapolis, MD. **Credit:** NASA

Already, it's disrupting people's lives, said research scientist **Ben Hamlington** [NASA/Jet Propulsion Laboratory (JPL)]. "It impacts your ability to go to work, to drop the kids off at daycare, to go to the grocery store."

Hamlington leads the NASA Sea Level Change team, which studies the roles that ocean, ice, and land play in high-tide flooding. In March 2019, the NASA team met in Annapolis with 35 local and state government officials to discuss the challenges coastal cities are facing and provide science and research to help them make decisions.

Future projections are gloomier. Without additional flood management efforts, the frequency of this kind of flooding is projected to double or triple by 2030, and could be as much as 15-fold higher by 2050. This means high-tide flooding could occur 180 days a year in some locations, "effectively becoming the new high tide," the report reads.

Plus, floodwater can travel up pipes, compromising both stormwater and wastewater systems. In Norfolk and Chesapeake, VA, lawn fertilizers get flushed by tidal floods from people's yards and into the Elizabeth River, feeding harmful algal blooms, said assistant professor **Derek Loftis** [Center for Coastal Resources Management with the Virginia Institute of Marine Science], who studies the issue.

Sea level rise can feel abstract, like something looming far off in the future. But if you want to see it happening in real-time, look no further than these floods.

"It's not an esoteric discussion any longer," Sweet said. "It's real."

What Drives It

Think of high-tide flooding as a layering of different processes on different time scales, said Hamlington. On the shortest time scale, you have the tides themselves, which are driven by the gravitational pull of the Moon. The highest high tides typically occur during full moons and new moons, when the Moon, the Sun, and Earth are nearly aligned. During these times, the pull is stronger as the gravity of the Sun reinforces the gravity of the Moon.

Winds can also influence how high the tides come in. The Chesapeake Bay, for example, is prone to winds from the north and the south. "Winds from the south shove water up the bay, and Northeasterly winds can pile up water regionally along much of the East coast, including the bay." Sweet said. "And we're not talking about extreme winds, we're talking about the kind of winds that we like when we go sailing: 15-, 20-knot winds."

Then there are the climate patterns like El Niño, which lead to higher-than-normal sea levels along both the U.S. East and West coasts. Subsidence, the settling or sinking of land, also has a powerful role to play. Subsidence partly stems from natural causes, like the compaction of sediments in the Mississippi Delta and the movement of land due to natural geologic processes, but also from the extraction of groundwater and natural gas along the Gulf coast.

And, of course, the most powerful driver is sea level rise itself. The ocean is rising at about 0.13 in (~3.3 mm) a year, mostly due to the melting of land-based ice and the thermal expansion of ocean water, according to NASA. This rate is accelerating over time, by about an additional 0.04 in (1 mm) per year roughly every decade.

Measuring High-Tide Flooding

The best flood projections must take all of these processes into account, and that requires a view from space, Hamlington said.

"Understanding the future of high-tide flooding is a little bit like a puzzle," Hamlington said. "We're trying to put together the pieces. And the satellites we have available really help us do that."

Hamlington's team relies on a suite of radar altimeter satellites to measure the height of the ocean surface. From an altitude of 830 mi (1336 km), these altimeters bounce signals off the ocean surface and measure the time it takes them to return to the spacecraft.

"To study large-scale climate signals like El Niño, we need to have a broad view of the ocean," Hamlington said. "The altimeters give us really accurate measurements of sea surface height on these very large scales."

They include the Jason-3 satellite, an international partnership between NOAA, NASA, the French government's National Centre for Space Studies, and EUMETSAT,[1] along with its predecessors, Jason-1, Jason-2 and TOPEX/Poseidon, which collectively form a consecutive record dating back to 1992. Launched November 21, 2020, Sentinel-6 Michael Freilich marks the latest satellite in the partners' efforts.

These observations combine with other satellite data and with continuous measurements from about 2000 tide gauges worldwide to fill in the pieces of that puzzle. The satellites fill in the gaps where the tide gauges are sparse.

Mapping Rising Tides

Satellite data also help scientists model and map high-tide flooding events. In coastal Virginia, for example, Loftis has helped create a model to predict the area's highest high-tide floods of the year, and has paired it with a large citizen science effort to validate the location of those floodwaters.

Over the years, he's recruited hundreds of volunteers-turned-citizen scientists to fan out along the coastline and validate his projections by marking the height of the floodwaters with GPS tags. The effort began in Norfolk, VA, but has expanded to volunteers across coastal Virginia and Maryland's Eastern shore. The team relies on the Landsat 7 and Landsat 8 satellites from NASA and the U.S. Geological Survey (USGS), the Terra satellite's Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and Moderate Resolution Imaging Spectroradiometer (MODIS) instruments, and NOAA's Geostationary Operational Environmental Satellite-16 (GOES-16) geostationary satellite, to evaluate the model after the flood. He also believes that a new 98-ft (30-m) mapping model that uses data from the NOAA–NASA Suomi National Polar-orbiting Partnership satellite and NOAA-20 satellites might be helpful in the future. Loftis

[1] The European Organisation for the Exploitation of Meteorological Satellites is an intergovernmental organisation created through an international convention agreed by a current total of 30 European Member States.

Photo 2. Ramsay Road, which runs along the cemetery on the campus of the U.S. Naval Academy, flooded more than 40 times in 2018 and 2019. **Credit:** David Kriebel

hopes these maps will help cities prepare for future floods as well as urban flood protection.

"There previously wasn't much of a frame of reference," Loftis said. "Now we've got a map with volunteer data that confirms yes, this is what we saw with tens of thousands of data points."

High-tide flooding is not just a beachfront problem. It's a problem that will increasingly impact urban areas like New York City, NY; Philadelphia, PA; Charleston, SC; and Miami, FL but also smaller communities along the coast, especially in back bays and estuaries, said professor of ocean engineering **David Kriebel** [U.S. Naval Academy]. It's likely to become a story of haves and have nots, he said. Some areas will have the means to afford the massive funding required to protect against it; others won't.

"I think we're going to end up with certain locations that are going to take big actions—New York City and Miami Beach are examples—and we're going to have other smaller communities that are going to have a hard time dealing with it," he said.

Building Defenses

Half a mile up the road from Downtown Annapolis, the U.S. Naval Academy is also beating back water. McNair Road runs along the perimeter of campus, separating the academy's indoor stadium from College Creek, a waterway that feeds into the Severn River, and eventually, the Chesapeake Bay. When the seawater gets high enough, it shoots up through the storm drains, flooding McNair Road, and at the same time, spills over onto Ramsay Road on the opposite side of the creek. Both roads have already flooded 20 times this year, and more than 40 times each in 2018 and 2019.

On a recent fall morning, Kriebel points out the many defenses the campus has built against rising water: A seawall built alongside the river, flood walls protecting campus buildings, and classroom floors and walls made of concrete or painted cinder block—materials more resistant to flooding than carpet, wood and drywall.

Across the river, at Ramsay Road, high water levels frequently flood parts of the road that run alongside the cemetery where Naval Academy alumni, including former Senator John McCain, are buried—see **Photo 2**. The cemetery itself is on a hill, so it's not in danger of flooding, but floodwater has been known to close the road on days that solemn services are planned.

And in addition to the water that floods over roads, there's the water lurking just below the road surface.

"When the water is just below the roadbed on the one side," Kriebel said, "it seeps through the gravel under the road and pops out the other side." On top of the 40-some flood events occurring each year, he added, "there are literally hundreds of high tides that are just a few inches below the road surface today."

At the Naval Academy, they're considering various flood protection options. One option at Ramsay Road is to abandon the road and relocate it. Another is to build another flood wall. But Kriebel suspects they'll choose a third option, to elevate the road by about a foot, and eventually raise the athletic field that runs alongside it too.

Still, he said, the water is rising fast, and much of this flood protection will only last for a few decades. At that point, additional measures will have to be taken.

"You can build walls, you can add inflow preventers and you can protect areas that are worth protecting, but eventually, water's going to find its way through the holes," Sweet said. "You're not really meant to hold back the tides." ■

NASA Funds Projects to Make Geosciences Data More Accessible

Sofie Bates, NASA's Goddard Space Flight Center, sofie.l.bates@nasa.gov

EDITOR'S NOTE: This article is taken from *nasa.gov*. While this material contains essentially the same content as the original release, it has been rearranged and wordsmithed for the context of *The Earth Observer*.

NASA has accumulated about 40 petabytes (PB) of Earth science data, which is about twice as much as all of the information stored by the Library of Congress. In the next five years, NASA's data will grow up to 250 PB—more than six times larger than what NASA has now.

The sheer amount of data provided by NASA gives scientists and the public the extensive Earth science information they need for informed research and decision-making. But that amount of data creates a slew of challenges, including how to store the data, how to get it into consistent and useable formats, and how to search massive datasets.

To help address these issues, NASA has funded 11 new projects as part of the agency's Earth Science Data Systems' Advancing Collaborative Connections for Earth Systems Science (ACCESS) program. Proposals submitted in 2019 and funded in 2020 focused on three areas: machine learning, science in the cloud, and open-source tools.

Earth scientists often work with data collected by NASA's space, airborne,[1] and ground observation missions. Before using all of those data for machine learning, however, they have to create large *training datasets*. For example, for machine learning to detect a forest in a new satellite image, the algorithm needs to be "trained" to detect forests. To do that, experts select and label forest areas in existing images and use that as the training dataset. Once the machine learning algorithm has been trained by looking at that dataset, the algorithm can distinguish forested areas in new satellite images.

Creating that training dataset can take months or even years—a problem that the geosciences community has dubbed the "training data bottleneck." For their ACCESS project, **David Roy** [Michigan State University] and his team are trying to expedite that process.

Roy's project aims to create a high-quality, high-resolution training dataset that other scientists can use to quickly determine which areas are burned or covered with trees. The project is using high-resolution satellite data collected almost every day by Planet's[2] CubeSat constellation, acquired as part of NASA's Commercial SmallSat Data Acquisition (CSDA) Program. Roy and his team will make the training dataset and software available through NASA's ACCESS program so that other researchers can create their own training datasets.

Another 2019 ACCESS project—led by **Fritz Policelli** [NASA's Goddard Space Flight Center]—focuses on machine learning with a different application. Policelli's team is creating a high-quality training dataset of stream widths to help other scientists measure river width and streamflow around the world—see **Figure**. These data track how much water is flowing through a river or stream over time, which has important applications for water resource management and monitoring floods.

Policelli's work will complement the data collected by the Surface Water and Ocean Topography (SWOT) mission, scheduled to launch in late 2021. NASA

continued on page 50

[1] To learn more, see "Flying in the 'Gap' Between Earth and Space: NASA's Airborne Science Program," in the September–October 2020 issue of *The Earth Observer* [**Volume 32**, **Issue 5**, pp. 4–14—*https://go.nasa.gov/2KSPTy5*].

[2] Planet is an Earth-imaging company based in San Francisco, CA.

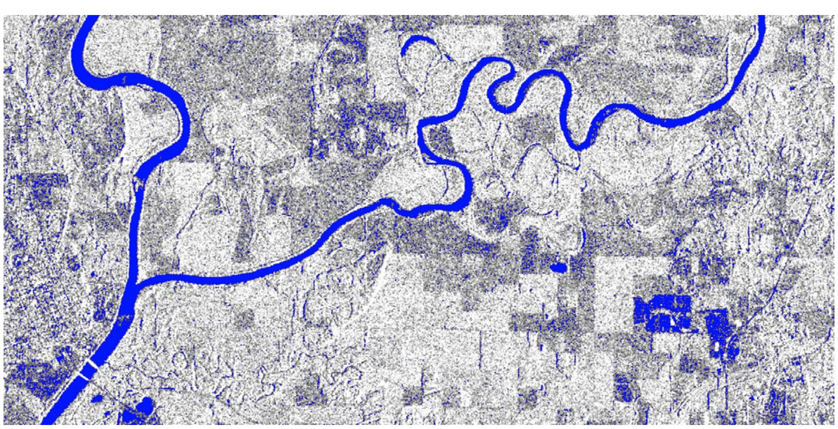

Figure. Policelli and his team are developing maps like this preliminary surface water map of the Ohio River to accurately measure river widths around the world, allowing other scientists to use these data and machine learning to estimate river flow rates. **Credit:** Image by Chandana Gangodagamage [University of Maryland]

NASA Earth Science in the News

Ellen Gray, NASA's Goddard Space Flight Center, Earth Science News Team, ellen.t.gray@nasa.gov

EDITOR'S NOTE: This column is intended to provide a sampling of NASA Earth Science topics reported by online news sources during the past few months. Please note that editorial statements, opinions, or conclusions do not necessarily reflect the positions of NASA. There may be some slight editing in places primarily to match the style used in *The Earth Observer*.

Climate Change Mapped: NASA Tracks How Arctic Animals React to "Out of Whack" Warming, November 22, *express.co.uk*. New NASA research has revealed that climate change is accounting for "extreme" shifts in animal migrations in the Arctic. Life for animals living in the unforgiving conditions of the Arctic is a precarious balancing act—from unseasonably warm springs to plunging autumnal temperatures—and annual variations signal to animals when to migrate, mate, and/or search for food. Even a shift of just a few days can have profound impacts on these animals and their environment. Research cofunded by the NASA Arctic-Boreal Vulnerability Experiment (ABoVE) has revealed that these seasonal timing changes are becoming ever more pronounced. Scientists studied data from the Arctic Animal Movement Archive (AAMA), which have been used to track nearly a hundred species from 1991 to the present. This information was then cross referenced with NASA temperature, rainfall, snowfall, and topographic data. The results revealed that Arctic animals' movement patterns are shifting in ways that will disrupt entire ecosystems.[1] Indications that the Arctic climate really is transforming include sea-ice shrinkage, variations in amounts of rainfall and snowfall, and even the Arctic tundra turning vivid shades of green. The team focused on examining eagle migrations, caribou populations, and a multispecies study focusing on several predator and prey species. In the eagle study, researchers analyzed when eagles left their wintering grounds to fly north for the summer, based on National Oceanic and Atmospheric Administration (NOAA) data collected over a decade—see **Photo**. On average, eagle migration started about a half day earlier each year—a change that, when compounded over 25 years, results in a shift of almost two weeks.

[1] To watch a time-lapse graphic of the movement patterns for various animals, visit *https://go.nasa.gov/33y1md8*.

NASA Satellite to Monitor Sea Level Rise, Effects of Climate Change over Next Decade, November 21, *usatoday.com*. A week after it sent four astronauts to the International Space Station, SpaceX launched the first of two satellites that will monitor sea level rise over the next decade. The Sentinel 6-Michael Freilich oceanography satellite is a joint venture between NASA, the European Space Agency, European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), and NOAA, named to honor the late director of NASA's Earth Science Division. It began a five-and-a-half-year mission to collect "the most accurate data yet on global sea level and how our oceans are rising in response to climate change," according to NASA. The mission also will collect information on atmospheric temperature and humidity to improve weather forecasts and climate models. The satellite headed into orbit on a SpaceX Falcon 9 rocket launched from California's Vandenberg Air Force base at 12:17 PM EST on November 21, 2020. A second satellite is expected to launch in coming years. Once in orbit, each satellite will collect sea level measurements "down to the centimeter for 90% of the world's oceans," according to NASA. This most recent effort to monitor sea level rise follows the 2016 launch of

Photo. Researchers release several eagles after affixing tags to track the eagles' movement. **Credit:** Bryan Bedrosian/Teton Raptor Center the U.S.-European Jason-3 satellite, which is currently providing observations of ocean topography. The Jason satellites have been monitoring global sea levels since 2001. While they have been able to track climate phenomena like El Niño and La Niña, the satellites have been unable to measure smaller sea level variations. The new satellites will collect measurements at higher spatial resolutions.

The Seasonal Ozone Hole over Antarctica Will Remain Active Well into November, November 18, *space.com*. The seasonal ozone hole over Antarctica will persist well into November, according to satellite and weather-balloon observations from NASA and NOAA. Ozone is a gas that in the stratosphere—one of its two natural regions in the atmosphere—acts like a "sunscreen" to life on Earth. In that region, ozone protects our planet from cancer-inducing ultraviolet radiation that also can damage plants and plankton. (The other natural location is much closer to the ground, in the troposphere, where the Sun's rays fuel photochemical reactions of ozone with pollution from vehicle and industrial emissions to generate smog.) The natural stratospheric ozone depletes when chlorine and bromine from human activities latch on to the ozone atoms and destroy them. Every winter in the Southern Hemisphere, the returning Sun's rays cause the interactions that erode the ozone. The erosion will continue in the cold temperatures until the approach of spring, according to NASA. "Persistent cold temperatures and strong circumpolar winds, also known as the polar vortex, supported the formation of a large and deep Antarctic ozone hole that should persist into November," NASA said in a statement October 30, 2020. "The annual Antarctic ozone hole reached its peak size at about 9.6 million mi^2 [24.8 million km^2], or roughly three times the area of the continental U.S., on September 20. Observations revealed the nearly complete elimination of ozone in a 4-mile-high [6.5-km] column of the stratosphere over the south pole," the agency added. The 2020 ozone hole is the twelfth largest by area as recorded in 40 years of satellite records, and has the fourteenth lowest amount of ozone as measured by balloon instruments, NASA said. The production of ozone, however, is much lower than it was in the year 2000—when the size of the hole peaked. The hole has been diminishing ever since 2000, due to declines in ozone-depleting chemicals, as regulated by the 1987 Montreal Protocol, NASA added.

Interested in getting your research out to the general public, educators, and the scientific community? Please contact ***Ellen Gray*** *on NASA's Earth Science News Team at* ellen.t.gray@nasa.gov *and let her know of upcoming journal articles, new satellite images, or conference presentations that you think would be of interest to the readership of* **The Earth Observer**.

NASA Funds Projects to Make Geosciences Data More Accessible

continued from page 48

and the Centre National d'Études Spatiales (CNES) are developing SWOT with contributions from the Canadian Space Agency (CSA) and United Kingdom Space Agency.

Among the data it collects, SWOT will measure stream flow rates around the world twice every 21 days. Policelli's work will fill in the gaps between SWOT's passes using stream width measurements from the European Space Agency's (ESA) Copernicus Sentinel-1 data and machine learning developed by his team.

Policelli's team is partnering with NASA's Alaska Satellite Facility Distributed Active Archive Center (ASF DAAC) at the Geophysical Institute at the University of Alaska, Fairbanks, which stores data collected by Sentinel-1 in the cloud. The new streamflow data will be stored, processed, analyzed, and distributed in that cloud, eliminating the problem of having to download massive data files. Prior to cloud storage and computing, geoscientists often had to plan their work schedules around waiting for large data files to download.

In addition to optimizing machine learning tools for geoscience research, another ACCESS funded project led by **Joe Hamman** [CarbonPlan[3]—*Technology Director*] seeks to make those tools open source and easily accessible in the cloud. His project will create tools that bridge the gap between software used to analyze geoscience data and software used in machine learning. For example, converting geospatial data, which includes location information, to a format that can be used more effectively in machine learning. All of the tools developed will be open source to help researchers process data from many different sources, including the NASA–U.S. Geological Survey (USGS) Landsat fleet, the NASA–ESA Jason satellites, and the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument aboard NASA's Terra and Aqua satellites.

Altogether, eleven projects were selected for funding through the 2019 ACCESS program. Each project incorporates methods to improve machine learning, science in the cloud, or open science. More information on all of the 2019 projects can be found at *https://go.nasa.gov/3mtPyQe*.

[3] CarbonPlan is a non-profit organization based in San Francisco, CA.

Earth Science Meeting and Workshop Calendar

NASA Community

NASA Community events will be updated in our next issue.

Global Science Community

January 10–15, 2021
AMS Annual Meeting, *virtual*
https://annual.ametsoc.org/index.cfm/2021

April 19–30, 2021
EGU General Assembly, *virtual*
https://www.egu21.eu

August 2021
AOGS 18th Annual Meeting, *virtual*
https://www.asiaoceania.org/aogs2021/public.asp?page=home.html

AGU 2020 Medal, Award, and Prize Recipients and Fellows Include Three NASA Earth Scientists

Each year, the American Geophysical Society (AGU) presents a variety of medals, awards, and prizes. Despite the pandemic, the tradition continued in 2020. This year's 36 honorees include a diverse list of scientists, leaders, educators, journalists, and communicators who have made outstanding contributions to the Earth and space sciences community. *The Earth Observer* would like to specifically acknowledge the two honorees on this list from NASA Centers—who work on Earth science research and/or applications.

Claire Parkinson [NASA's Goddard Space Flight Center (GSFC)—*Aqua Project Scientist*] is the recipient of the *Roger Revelle Medal* in recognition of her myriad scientific contributions as well as her sustained impact within the Earth and space sciences community.

Vid Chirayath [NASA's Ames Research Center—*Airborne Science Program*] is the recipient of the *Charles S. Falkenberg Award* in recognition of his contributions to the quality of life, economic opportunities, and stewardship of the planet through the use of Earth science information, and to increasing public awareness of the importance of understanding our planet.

We extend congratulations to Claire, Vid, and all of the other 2020 AGU medal, award, and prize winners. (The full list can be viewed at *https://eos.org/agu-news/announcing-the-2020-agu-union-medal-award-and-prize-recipients*.)

In addition, **Ralph Kahn** [GSFC—*Senior Research Scientist*] is one of 62 people selected as a *2020 AGU Fellow*. This is a high honor that AGU bestows upon fewer than 0.1% of its members to recognize their dedication and sacrifice and to acknowledge their roles as global leaders and experts who have advanced our understanding of the geosciences.

Congratulations to Ralph and all of the other 2020 AGU Fellows. (The full list of can be found at *https://eos.org/agu-news/2020-class-of-agu-fellows-announced*.)

The 2020 AGU medal, award, and prize winners and fellows were recognized in a ceremony that took place December 9, 2020, during the AGU's virtual Fall Meeting.

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Article submissions, contributions to the meeting calendar, and other suggestions for content are welcomed. Contributions to the calendars should contain date, location (if meeting in person), URL, and point of contact if applicable. Newsletter content is due on the weekday closest to the first of the month preceding the publication—e.g., December 1 for the January–February issue; February 1 for March–April, and so on.

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