National Aeronautics and
Space Administration

2019 Annual Earth Report

Science Technology Office

Executive Summary

As you'll read in the pages that follow, 2019 was another full and productive year for technology development at the NASA Earth Science Technology Office (ESTO), with numerous successes advancing new technologies for Earth science as well as the competitive selection of new projects.

In fiscal year 2019 (FY19), ESTO continued to build upon its 20-year heritage of technology development and infusion. This year, 39% of active ESTO technology projects advanced at least one Technology Readiness Level, and of the 836 completed projects in the ESTO portfolio, 32% have already been infused into Earth observing missions, operations, or commercial applications. We are particularly proud to report that nearly 100 students – high school through PhD – were directly involved in ESTO-funded projects this year.

In January 2018, the National Research Council (NRC) released the second decadal survey for Earth science: Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space. As was the case with the 2007 decadal survey, ESTO investments are already well underway to directly support all of the recommended measurements.

In September 2019, ESTO selected 22 new projects through a competitive solicitation under the Advanced Information Systems Technology (AIST) program, and additional awards are expected in October 2019 under the Instrument Incubator Program (IIP) solicitation. We welcome these new cohorts of technologists and look forward to the contributions they will usher forward, ensuring a bright future for Earth science.

Pamela S. Millar
Program Director

Robert A. Bauer
Deputy Program Director

A SpaceX Falcon 9 rocket, carrying the Spaceflight SSO-A: SmallSat Express, launched from Space Launch Complex-4E at Vandenberg Air Force Base, CA, on Dec. 3, 2018. ESTO's CSIM CubeSat was aboard. (See p. 25) Credit: SpaceX

About ESTO

As the technology development function within NASA's Earth Science Division, the Earth Science Technology Office performs strategic planning and manages the development of a broad range of nascent technologies for future science measurements. ESTO employs an open, flexible, science-driven strategy and relies on competition and peer review to produce the best cutting-edge technologies, from advanced sensors aboard miniature satellites to software tools that digest and analyze large datasets.

Our approach to Technology Development:

- **Strategy:** Engage with the Earth science community to plan investments through careful analyses of science requirements
- **Selection:** Fund technology development through periodic, competitive solicitations and partnership opportunities
- **Management:** Review and advise funded technology projects on progress and performance
- **Infusion:** Encourage and facilitate the use of mature technologies in science measurements

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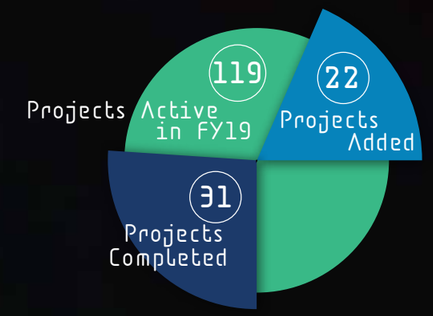
By The Numbers FY 19



2019 Metrics

With 836 completed technology investments and a portfolio during FY19 (October 1, 2018, through September 30, 2019) of 119 active projects, ESTO drives innovation, enables future Earth science measurements, and strengthens NASA's reputation for developing and advancing leading-edge technologies. To clarify ESTO's FY19 achievements, what follows are the year's results tied to ESTO's performance metrics.

GOAL 1

Annually advance 25% of currently funded technology projects at least one Technology Readiness Level (TRL).

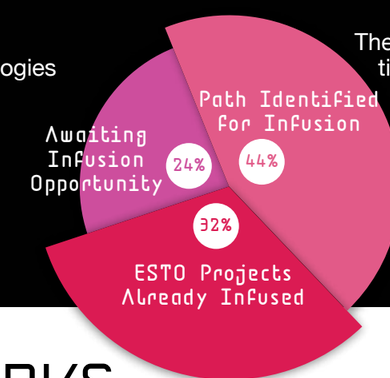
Percentage of Active Projects that advanced at least 1 TRL during each Fiscal Year.

FY19 Result

39% of ESTO technology projects funded during FY19 advanced one or more TRLs over the course of the fiscal year. Nine of these projects advanced more than one TRL. Although the percentage of TRL advancements tends to be higher in years with large numbers of completing projects, ESTO has consistently met or exceeded this metric in every fiscal year since inception. The average annual TRL advancement for all years going back to 1999 is 41%.

GOAL 2

Mature at least three technologies to the point where they can be demonstrated in space or in a relevant operational environment.



FY19 Result

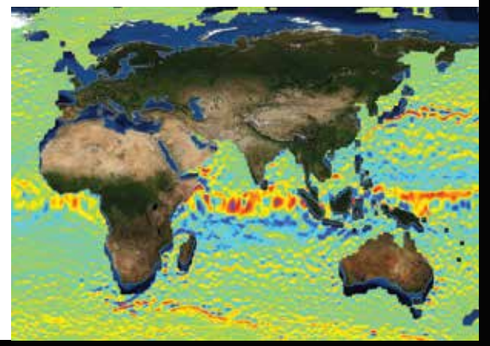
The chart to the left shows ESTO's all-time infusion success drawn from 836 completed projects through the end of FY19. In this fiscal year, at least five ESTO projects achieved infusion into science measurements, airborne campaigns, data systems, or follow-on development activities. Three notable examples follow.

OCEANWORKS

OceanWorks (Principal Investigator: Thomas Huang, Jet Propulsion Lab) is a collaborative information systems project working to establish a data analytics platform for ocean science. Oceanographers and other researchers rely on data centers like the Physical Oceanographic Data Active Archive Center (PO.DAAC) at the Jet Propulsion Lab to search for relevant sets of data and then download and analyze the data off-line. This approach works well when the data sets are manageable. As more ocean measurements generate large volumes of new data this workflow becomes less feasible.

For example, NASA's Surface Water and Ocean Topography (SWOT) mission, slated for launch in 2021, is expected to generate over 20 petabytes of data in just three years. OceanWorks has established the open source Apache Science Data Analytics Platform (SDAP) at PO.DAAC to facilitate web-based analysis of massive data sets, enabling "big data" ocean science from anywhere. Visit https://sdap.apache.org/ to learn more.

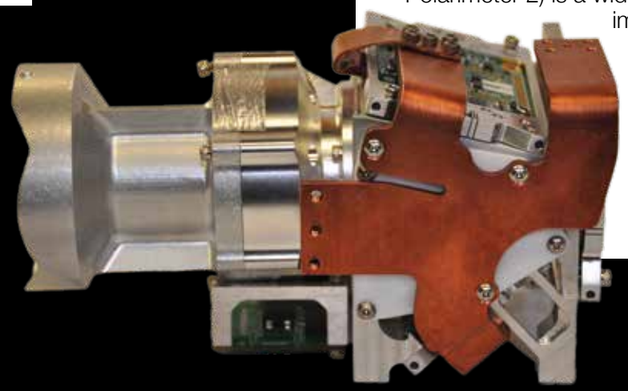
▼ **OceanWorks data product displaying MODIS data of the geographic distribution of chlorophyll-a in October 2003. Credit: JPL**



GOAL 2(cont.)

HARP/PACE

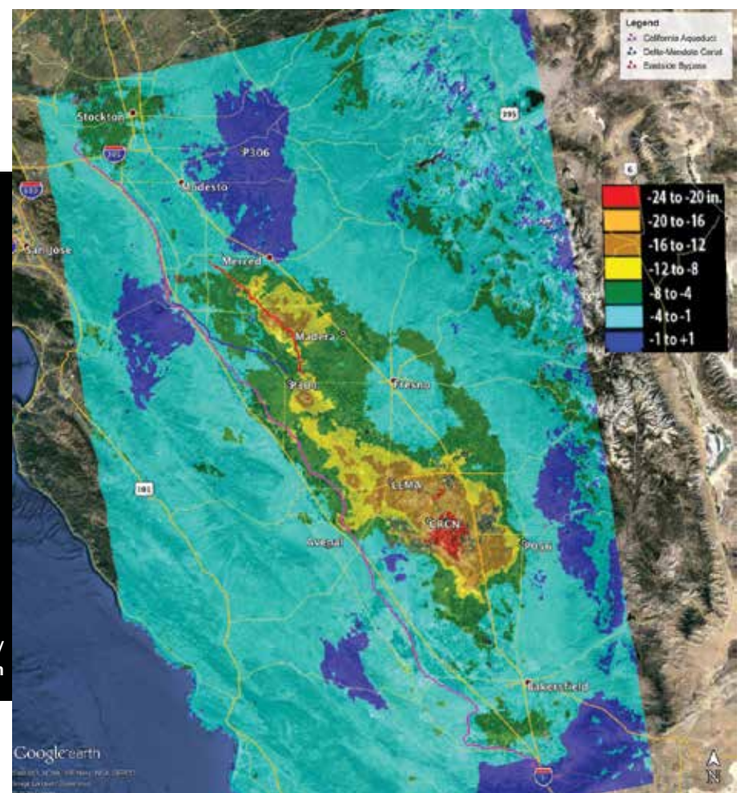
The NASA Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission is scheduled to launch in 2022 and will include an instrument to measure aerosol and cloud properties. The HARP2 (Hyper-Angular Rainbow Polarimeter 2) is a wide-angle imaging polarimeter with direct heritage from the HARP CubeSat (Principal Investigator: Vanderlei Martins, University of Maryland Baltimore County), a technology validation project slated to launch in November 2019. Once on orbit, HARP will demonstrate its ability to provide science-quality multi-angle imaging data of clouds and aerosols at four wavelengths and further prove the technology for the HARP2 instrument on PACE.



◀ **HARP polarimeter payload during mechanical fit check. Credit: Vanderlei Marin, UMBC**

Subsidence

In 2017, the California Department of Water Resources commissioned NASA's Jet Propulsion Lab to collect and analyze airborne and satellite radar data to assess land subsidence in the Central Valley area. Subsidence related to groundwater pumping is a constant concern for state water managers. An ESTO-funded project – Agile Big Data Analytics of High Volume Geodetic Data Products (Principal Investigator: Hook Hua, Jet Propulsion Lab) – helped to create the maps for the analysis, which identified areas that are sinking the fastest.



▶ **Image Credit: European Space Agency/ NASA-JPL/Caltech/Google Earth**

GOAL 3

Enable a new science measurement or significantly improve the performance of an existing technique.

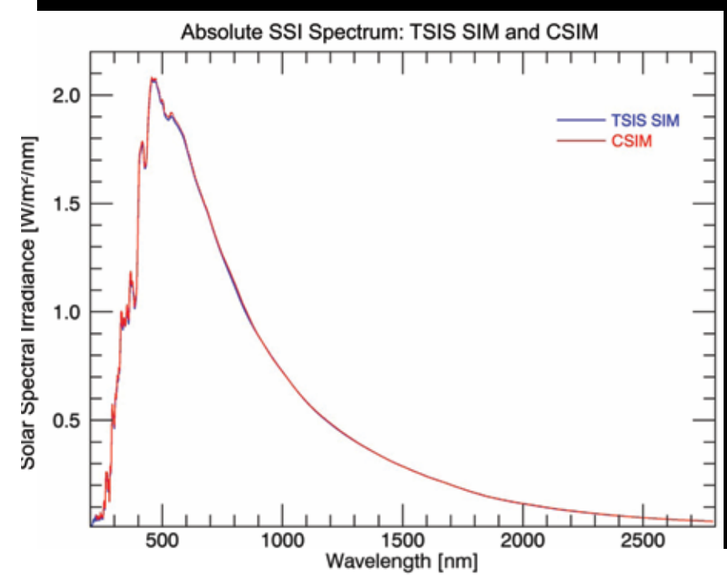
FY19 Result

Compact Solar Irradiance Monitor

Built at the Laboratory for Atmospheric and Space Physics in Boulder, CO, the Compact Spectral Irradiance Monitor (CSIM) is an ultra-compact instrument that makes measurements of solar spectral irradiance (SSI) – the incoming energy from the Sun – across the 200-2400 nm spectrum. SSI is a critical measurement for the establishment of benchmark climate records.

Launched in December 2018 aboard a SpaceX Falcon 9 rocket, the CSIM instrument design marks a significant departure from the previous SSI instruments, achieving large reductions in mass, volume, and power requirements, and enabling a flight-qualified instrument on a 6-unit CubeSat about the size of a shoebox. With operations nearing the one-year mark, CSIM has demonstrated its performance against measurements made by the SSI sensor aboard TSIS-1 (Total and Spectral Solar Irradiance Sensor) currently on the International Space Station. In September 2019, the project team calibrated the CSIM data and found that it compared exceptionally well to the TSIS-1 data, with average difference at less than 1%.

The differences in hardware are stark, however: Compared to TSIS-1, CSIM is just 1/10th the mass, 1/20th the volume, and uses 1/4th the power to operate. Several innovations enabled these reductions. The electronic substitution radiometer, which provides the exacting onboard calibration for CSIM, was radically reduced through the use of carbon nanotubes as the light absorber. And a rotating prism mechanism allows for precise wavelength scanning as well as calibration without the need for large optics. (See more on p. 25.)



◀ **Solar spectral irradiance agreement between the CSIM spectrum and TSIS-1's 300 – 2400 nm spectrum (< 1% difference). Both TSIS-1 and CSIM have calibration tied to standards set by the National Institute of Standards and Technology. Credit: E. Richard, Laboratory for Atmospheric and Space Physics**

Observation Tech

Carefully developed instrument and component technologies can reduce the risk and cost of new scientific observations with extended capabilities. ESTO's strategy for observation technologies focuses on new measurement approaches that can enable improved science capabilities and technologies to reduce the overall volume, mass, and operational complexity in observing systems. Developing and validating novel observation technologies before mission development improves their acceptance and infusion by mission planners and significantly reduces cost and schedule uncertainties. ESTO's Observation Technology investments are divided among three main programs: the Instrument Incubator Program, Advanced Component Technologies, and Sustainable Land Imaging-Technology.

Instrument Incubator Program

The Instrument Incubator Program (IIP) provides funding for new instrument and observation techniques, from concept to breadboard and flight demonstrations. Instrument technology development of this scale, outside of a flight project, consistently leads to smaller, less resource-intensive instruments that reduce the costs and risks of mission instrumentation.

35 Projects Active in FY19

7 Projects Graduated

Prototype Laser for an OH Integrated Path Differential Absorption Lidar – Thomas Hanisco, Goddard Space Flight Center

A Compact Adaptable Microwave Limb Sounder (CAMLS) for Atmospheric Composition – Nathaniel Livesey, Jet Propulsion Laboratory

MISTiC Winds: Midwave Infrared Sounding of Temperature and humidity in a Constellation for Winds – Kevin Maschhoff, BAE Systems

Snow and Water: Imaging Spectroscopy for coasts and snow cover (SWIS) – Pantazis Mouroulis, Jet Propulsion Laboratory

Three Band Cloud and Precipitation Radar (3CPR) – Gregory Sadowy, Jet Propulsion Laboratory

Triple-Pulsed 2-Micron Direct Detection Airborne Lidar for Simultaneous and Independent CO2 and H2O Column Measurement Novel Lidar Technologies and Techniques with Path to Space – Upendra Singh, Langley Research Center

An Instrument Concept for Combined Observations of GNSS and Astronomical Sources Through a Standard Signal Path for Geodetic Applications – Jonathan York, University of Texas, Austin

Advanced Component Technologies

Advanced Component Technologies (ACT) implements technology developments to advance state-of-the-art instruments. The ACT program funds the research, development, and demonstration of component- and subsystem-level technologies to reduce the risk, cost, size, mass, and development time of missions and infrastructure.

23 Projects Active in FY19

4 Projects Graduated

Proof-of-concept and feasibility demonstrations for an avalanche photodiode/photoelastic modulator-based imaging polarimeter – David Diner, Jet Propulsion Laboratory

Modular Dual-band Ku/Ka Antenna Tile with Digital Calibration (K-Tile) – James Hoffman, Jet Propulsion Laboratory

Nano-scale Micromachined Doped Silicon Thermopile Detector Development for Thermal Land Imaging Applications – Alicia Joseph, Goddard Space Flight Center

A Compact Trace Gas Lidar for Simultaneous Measurements of Methane and Water Vapor Column Abundance – Haris Riris, Goddard Space Flight Center

Sustainable Land Imaging – Technology

6 Projects Active in FY19

For over 40 years, the Landsat series of satellites has been providing a continuous stream of moderate resolution, multispectral images that have been used by a broad range of specialists to analyze our world. To continue the mission of Landsat, NASA initiated the **Sustainable Land Imaging – Technology (SLI-T)** program to explore innovative technologies to achieve Landsat-like data with more efficient instruments, sensors, components, and methodologies. Through SLI-T, ESTO currently manages six projects focused on science enhancement and reductions in instrument volume, mass, and power usage.

Advanced Information Systems Technology

60 Projects Active in FY19

8 Projects Graduated

Advanced information systems play a critical role in the collection, handling, management, and analysis of the vast amounts of Earth science data, both in space and on the ground. Advanced computational systems and technology concepts that enable the capture, transmission, and dissemination of terabytes of data are essential to NASA's vision of a distributed observational network. ESTO's **Advanced Information Systems Technology (AIST)** program employs an end-to-end approach to develop these critical technologies — from space where the information pipeline begins, to the end user where knowledge is advanced.

Next Generation UAV Based Spectral Systems for Environmental Monitoring – Petya Campbell, University of Maryland, Baltimore County

Computer Aided Discovery and Algorithmic Synthesis for Spatio-Temporal Phenomena in InSAR – Victor Pankratius, MIT

Generative models to forecast community reorganization with climate change – Jennifer Swenson, Duke University

Software workflows and tools for integrating remote sensing and organismal occurrence data streams to assess and monitor biodiversity change – Walter Jetz, Yale University

Exploiting arc-GIS in the Analytic Center Framework – Christine White, ESRI

Remote Sensing Data Analysis and Uncertainty Quantification System Design – Amy Braverman, Jet Propulsion Laboratory

Machine Learning experiment with Lidar Science Data Processing – Matt McGill, Goddard Space Flight Center

Arctic Sea Ice Feature Extraction Pipeline – Chris Polashenski, Dartmouth College

In-space Validation of Earth Science Technologies

9 Projects Active in FY19

NASA's vision for future Earth observations necessitates the development of emerging technologies capable of making new or improved Earth science measurements. Promising new capabilities, however, bring complexity and risk, and for some technologies there remains a critical need for validation in the hazardous environment of space. ESTO's **In-Space Validation of Earth Science Technologies (InVEST)** program facilitates the space demonstration of technology projects that cannot be sufficiently evaluated on the ground or through airborne testing. Once validated in space, technologies are generally more adoptable, even beyond their intended use.

22 New AIST Projects to Start in FY20

Cloud-Based Analytic Framework for Precipitation Research (CAPRi) – John Beck, University of Alabama, Huntsville

StereoBit: Advanced Onboard Science Data Processing to Enable Future Earth Science – James Carr, Carr Astronautics Corporation

Creation of a Wildland Fire Analysis: Products to Enable Earth Science – Janice Coen, University Corporation For Atmospheric Research

Quantifying Uncertainty and Kinematics of Earthquake Systems (QUAKES-A) Analytic Center Framework – Andrea Donnellan, Jet Propulsion Laboratory

Multi-Scale Methane Analytic Framework – Riley Duren, Jet Propulsion Laboratory

Towards the Next Generation of Land Surface Remote Sensing: A Comparative Analysis of Passive Optical, Passive Microwave, Active Microwave, and LiDAR Retrievals – Barton Forman, University of Maryland, College Park

Preparing NASA for Future Snow Missions: Incorporation of the Spatially Explicit Snow Model in LIS – Ethan Gutmann, University Corporation For Atmospheric Research

Surrogate Modeling for Atmospheric Chemistry and Data Assimilation – Daven Henze, University of Colorado, Boulder

Predicting What We Breathe: Using Machine Learning to Understand Air Quality – Jeanne Holm, City of Los Angeles

Smart On-Demand Analysis of Multi-Temporal and Full Resolution SAR ARDs in Multi-Cloud & HPC – Hook Hua, Jet Propulsion Laboratory

AMP: An Automated Metadata Pipeline – Beth Huffer, Lingua Logica LLC

Valid Time-Series Analyses of Satellite Data to Obtain Statistical Inference about Spatiotemporal Trends at Global Scales – Anthony Ives, University of Wisconsin, Madison

An Analytic Center for Biodiversity and Remote Sensing Data Integration – Walter Jetz, Yale University

Development of the High Performance Version of GEOS-Chem (GCHP) to Enable Broad Community Access to High-Resolution Atmospheric Chemistry Modeling in Support of NASA Earth Science – Randall Martin, Washington University in St. Louis

SPCTOR: Sensing-Policy Controller and OptimizeR – Mahta Moghaddam, University of Southern California

NASA Evolutionary Programming Analytic Center (NEPAC) for Climate Data Records, Science Products and Models – John Moisan, Goddard Space Flight Center

D-SHIELD: Distributed Spacecraft with Heuristic Intelligence to Enable Logistical Decisions – Sreeja Nag, Ames Research Center

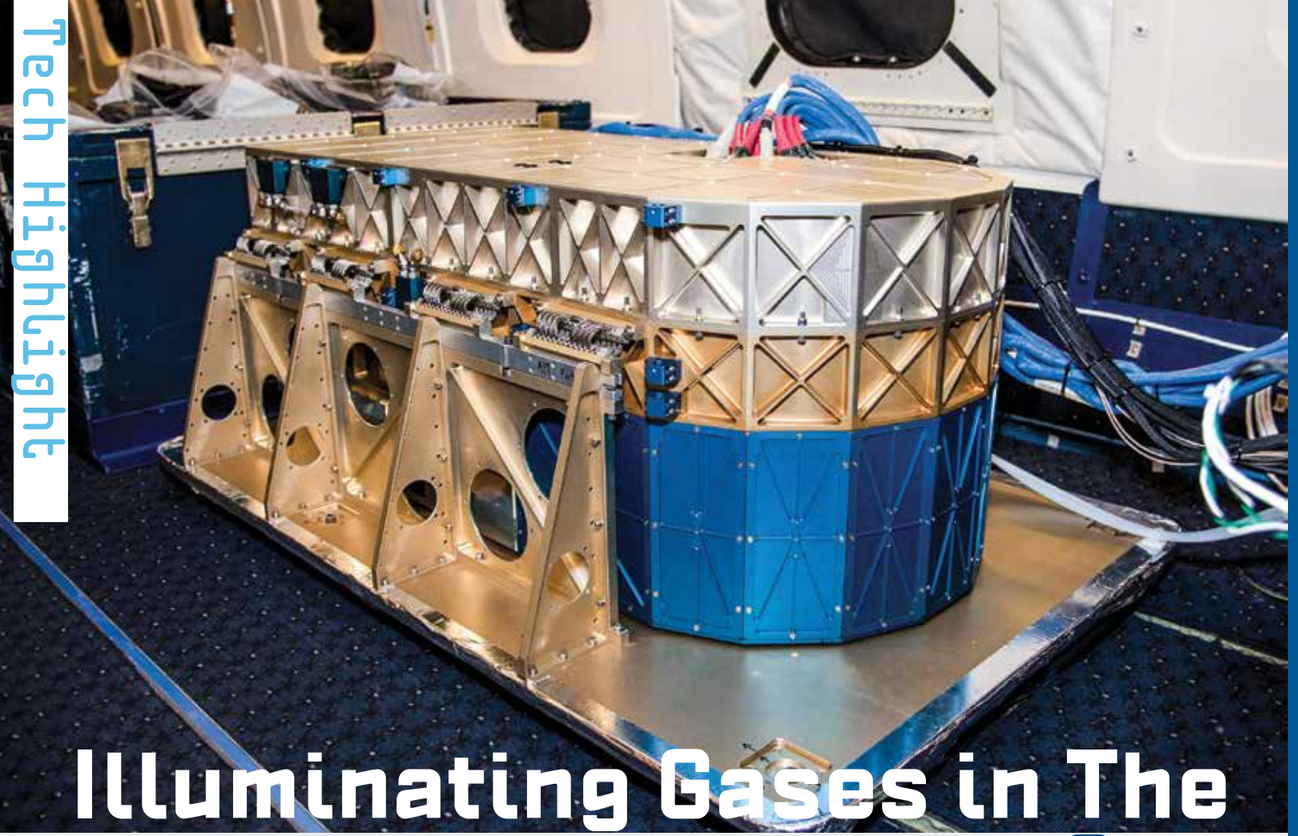
A Science-Focused, Scalable, Flexible Instrument Simulation (OSSE) Toolkit for Mission Design – Derek Posselt, Jet Propulsion Laboratory

Supporting Shellfish Aquaculture in the Chesapeake Bay Using Artificial Intelligence to Detect Poor Water Quality Through Sampling and Remote Sensing – Stephanie Schollaert Uz, Goddard Space Flight Center

The Bridge from Canopy Condition to Continental Scale Biodiversity Forecasts, Including the Rare Species of Greatest Conservation Concern – Jennifer Swenson, Duke University

On-Demand Geospatial Spectroscopy Processing Environment on the Cloud (GeoSPEC) – Philip Townsend, University of Wisconsin, Madison

Mining Chained Modules in Analytic Center Framework – Jia Zhang, Carnegie Mellon University



Illuminating Gases in The Sky

Whether idyllic floating cotton balls on an otherwise blue sky or ominous grey swirls that block the sun, clouds all begin as an invisible dot of water vapor. This elusive gas has been tricky to measure and track – until now. Research scientists at NASA's Langley Research Center created an airborne instrument that can directly measure water vapor and aerosols in the atmosphere. The new data will help check the accuracy of satellite measurements and improve weather and climate forecasts.

The instrument is called the High Altitude Lidar Observatory (HALO). It uses light detection and ranging (lidar), which works by shooting a pencil-thin laser beam through the atmosphere. The intensity of the signal reflected back to the lidar instrument gives the team the information they need to directly measure water vapor as well as aerosol and cloud profiles.

Water vapor is the most abundant and potent greenhouse gas in the atmosphere. It warms the air by trapping heat emitted from Earth but also cools by forming bright clouds that reflect heat radiated by the sun. HALO's data will help scientists as they research the extent of each of these processes, said Amin Nehrir, a research scientist and HALO's principal investigator.

HALO flew over the Pacific Ocean on April 15, 2019 aboard a DC-8 Airborne Science Laboratory based at NASA's Armstrong Flight Research Center in Edwards, California as part of a series of validation flights that took place when the European Space Agency's ADM Aeolus passed over the eastern Pacific.

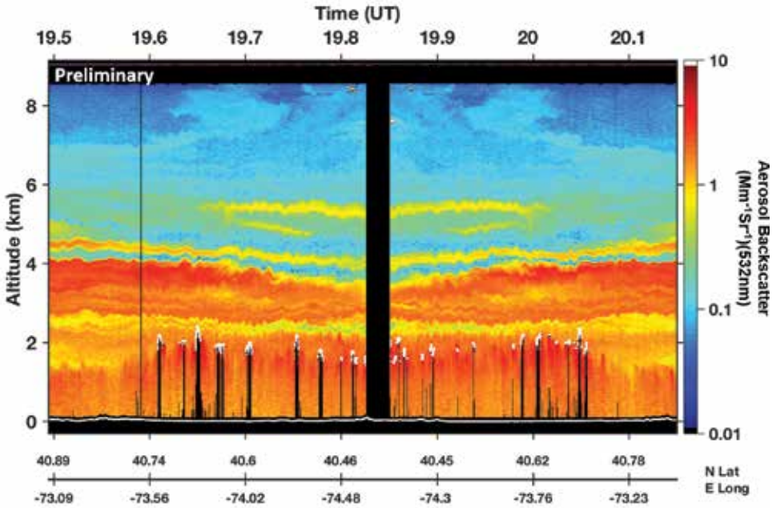
The ADM-Aeolus is the first satellite to profile wind speeds on a global scale from space, and it also collects aerosol data. HALO's aerosol measurements were used to validate the satellite, and its water vapor measurements gave scientists a more comprehensive picture of the atmosphere, helping the team prepare for future airborne campaigns dedicated to atmospheric dynamic processes.

HALO's Differential Absorption Lidar (DIAL) uses state-of-the-art lasers in a significantly more compact form than its 25-year-old predecessor, the Lidar Atmospheric Sensing Experiment (LASE). HALO is 5 percent the volume and 20 percent the weight of LASE.

HALO is also a modular instrument that can also be configured to measure methane, which is another potent greenhouse gas, in addition to aerosols, and cloud and ocean profiles. The modular set-up allows the team to reconfigure the instrument in a matter of days.

HALO is looking to participate in future severe storm and Arctic field campaigns, where small variations in moisture can seed or prevent cloud formation depending on the surrounding environment. These clouds have a large impact on the Arctic radiation budget, which drives how quickly the Arctic warms and releases methane from the melting tundra. HALO's ability to measure methane will help scientists understand where and how much Arctic methane is entering the atmosphere.

◄ The HALO instrument head, which houses the lidar, installed on the DC-8 airborne science laboratory at NASA Armstrong Flight Research Center. Credit: Lauren Hughes / NASA



► HALO collected this data set showing aerosols suspended in the atmosphere over Long Island Sound in Summer 2018. Reds/oranges indicate a higher concentration of aerosols and greens/blues show fewer aerosols. The white specks are caused by clouds, which block the laser beam from reaching the surface and cause a black line in lieu of data. Credit: Amin Nehrir / NASA

Decoding Extreme Weather at the Poles

A new software connects scientists to the Arctic.

A silvery metal tube jutting out of thick ice stands alone amid a vast landscape of endless white in Antarctica.

This 30-foot tube, equipped with weather sensors poking out at perpendicular angles, is able to record Arctic temperature, pressure, wind speed, and other conditions, but less adept at formatting and sharing its data with scientists.

An ESTO-funded technology aims to fix that. With new software, scientists will be able to easily access weather data in the Arctic, allowing them to better understand weather locally and better assess climate change impacts globally.

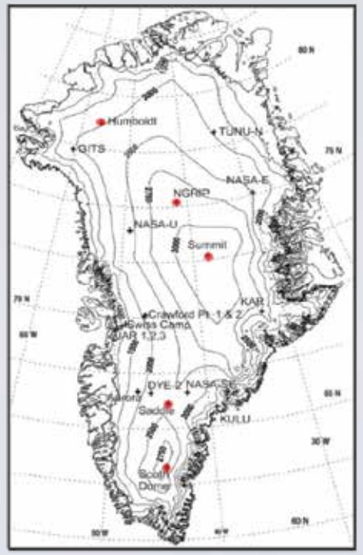
Various setups similar to the shiny metal tube, called Automated Weather Stations, or AWS, cover Antarctica and Greenland. Although they collect vital data, AWS networks use different "home-brewed" data formats from the 1980s and '90s, making them difficult to parse, Charlie Zender, a professor and atmospheric physicist with the University of California, Irvine, says. "The data are like a kid's bedroom after a sleepover."

To fix this, Zender and his team created software that converts messy AWS data to a new, clean format. Zender dubbed the software "JAWS," which stands for "Justified Automated Weather Station," in homage to the "justify" tool on Microsoft Word, which formats mismatched paragraphs into perfect rectangles.

Zender and his team delivered this free software, funded by the ESTO, to climate database managers who can then make AWS data widely available and accessible for scientists. The goal is to help scientists answer pressing questions, like what's causing Greenland's ice sheet to melt, Zender says.

The Greenland ice sheet is crucial to global climate. It sits at a high elevation, covers a large area storing a substantial volume of fresh water, and it is extremely reflective, bouncing the sun's energy away from Earth.

Greenland's AWS data is valuable but not easily usable right now, Walt Meier, a Senior Research Scientist with the National Snow and Ice Data Center, says. JAWS will make data "more adaptable and usable for a broader audience," Meier says. In particular, climate modelers will be able to incorporate these data into their formulas.

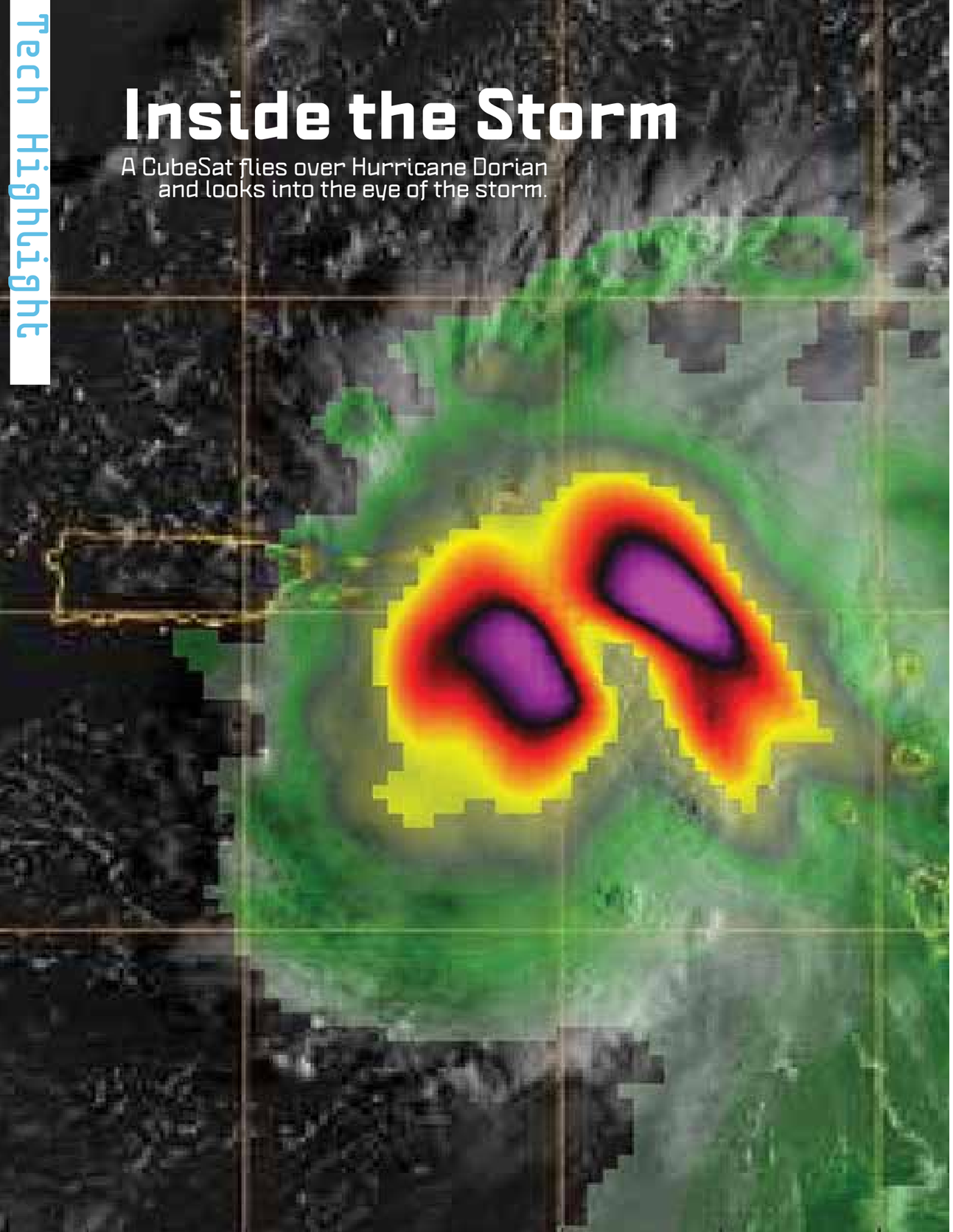


▲ **Location and elevation of the Greenland Climate Network (GC-Net) Automatic Weather Stations (AWS). Credit: Wang and Zender**

◀ **The Swiss Camp automatic weather station in Greenland. Credit: GC-Net**

Inside the Storm

A CubeSat flies over Hurricane Dorian and looks into the eye of the storm.



While Hurricane Dorian took aim at the Florida Coastline in early September 2019, a tiny satellite was orbiting overhead demonstrating that it had the science capabilities to peer inside the storm. TEMPEST-D (Temporal Experiment for Storms and Tropical Systems Demonstration) is a 6U CubeSat that was launched in May 2018 and has since provided detailed looks into several global weather systems.

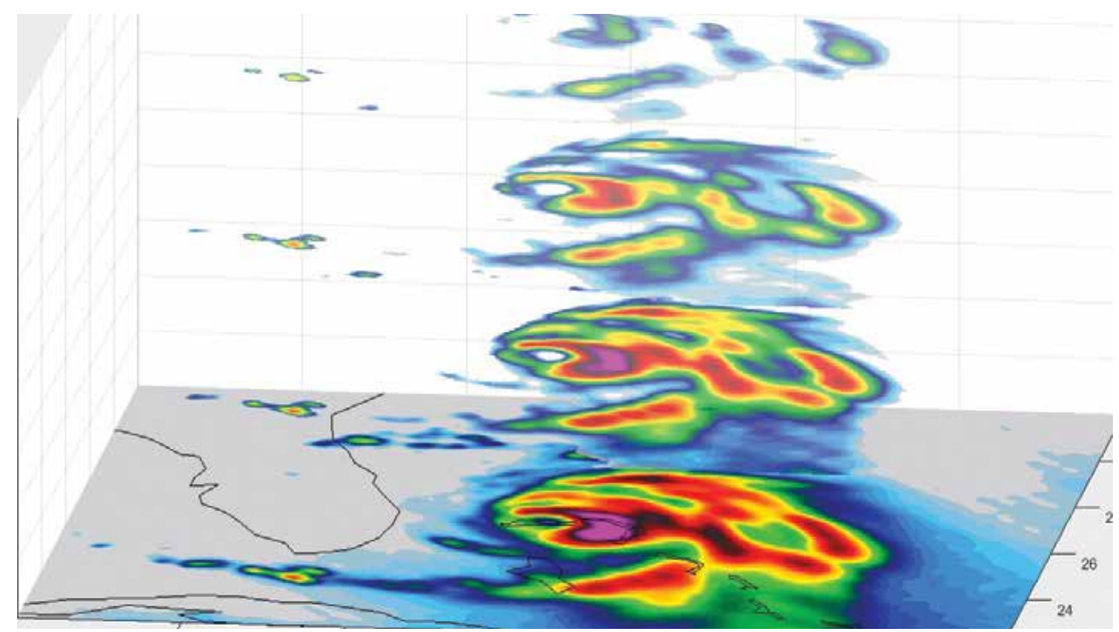
Using a passive millimeter-wave radiometer, TEMPEST-D scans the Earth with five frequency channels from 87 to 181 GHz, each channel mapping a vertical slice of a storm system at a corresponding altitude. The resultant data product displayed the interior structure of Hurricane Dorian, revealing areas of heavy rain and moisture being pulled into the storm.

TEMPEST-D's maps of the hurricane were closely correlated to data retrieved from NASA's CloudSat mission and the Atmospheric Infrared Sounder (AIRS) aboard the Aqua satellite. These instruments measure different attributes of the storm, and the combined information gives scientists and meteorologists an increasingly detailed picture of storms like Dorian.

Developed by PI Steve Reising at Colorado State University, TEMPEST-D hopes to prove that the low-cost CubeSat platform could enable a train of similar satellites that work together to track storms. A constellation of TEMPEST-Ds could one day display the temporal evolution of clouds, which would improve global storm coverage and forecasting and constrain one of the largest sources of uncertainty in climate models.

◀ Hurricane Dorian off the coast of Puerto Rico as seen by the small satellite TEMPEST-D. The colors in the image reveal the heavy rain and moisture inside the storm. The least intense areas of rainfall are shown in green and most intense are yellow and pink. Credits: NASA/JPL-Caltech/NRL-MRY

▼ Map showing vertical slices of the storm produced by TEMPEST-D's five-channel radiometer. Credits: NASA/JPL-Caltech



Helping Water Managers in a Warming World

How does global climate change play out locally in your community? A new NASA tool charts out what rising world temperatures will mean for local water resources.

To help water managers prepare for climate change-related impacts to water systems, an ESTO-funded team led by researchers at the National Center for Atmospheric Research in Boulder, Colorado is creating tools to make global climate change predictions local.

The effort aims to help water managers more easily understand how climate change compromises water security for communities, said Andy Wood, a scientist at NCAR leading the effort.

As winter precipitation that once fell as snow changes to rain, water flows into reservoirs, lakes and rivers at different times of the year than it has historically, said Jeff Arnold, a co-investigator on the project and a scientist with the U.S. Army Corps of Engineers (USACE). The USACE wants to know how much change to expect across the U.S. in the next 50 to 100 years, Arnold said, since that can impact how the agency operates its infrastructure, like dams and hydropower plants.

To bring water managers localized information, Wood's team is creating and sharing software, maps and datasets that localize global projections.

"We have changes coming out of global climate models that tell us really big-picture patterns," said Ethan Gutmann, a co-lead and scientist at NCAR. The global view may reveal how the atmosphere is likely to change, but it doesn't necessarily get down to how a specific basin is going to change, Gutmann said, because the global models run at a low spatial resolution.

To overcome this issue, Gutmann downscaled the global model climate projections, which means that instead of looking at an area that measures 100 by 100 miles, or approximately the size of the state of Maryland, he zoomed in on an area that's 5 by 5 miles, which is roughly the size of Disney World in Orlando, Florida. The team then connected Gutmann's model outputs to the NASA Land Information System to help characterize the downscaled climate change impacts on water resources.

"We are supporting the infrastructure to make the climate simulations and climate downscaling work much easier to set up for new groups interested in this kind of analysis," Gutmann said.

To make the work more meaningful and accessible to water managers, the team included and reached out to them from the start of the project.

"We really need to resonate with people so they don't just see the uncertainty [associated with projections] and say, this is just too much, I'm not going to use this information," said Julie Vano, a scientist and team member at NCAR.

Vano gathered feedback from water managers to understand their needs and concerns. For instance, in the Pacific Northwest, water managers have to decide how much water to release for hydropower generation and other uses based on how much snow melt will feed the system. Since they make this decision every year at the same time, they need to know whether potential long term changes in the seasonality of water supply could lead to changes in the best way to manage river flows.

The team's hope is that the new tools and data sets that come out of this project will allow them to characterize the uncertainties for smaller regions, so that water managers can make more informed decisions for the uncertain future.

Aiming High to Look at Clouds

A shoebox-sized instrument is expected to give researchers unprecedented insights into the ice crystals that form the wispy clouds that float high in the sky and play an important, but little-understood role in Earth's climate.

The instrument, called SWIRP — short for the compact Submm-Wave and LWIR (longwave infrared) Polarimeters for Cirrus Ice Properties — combines for the first time multiple wavelengths to obtain information about the ice crystals making up cirrus clouds. The instrument will help scientists understand their role in regulating Earth's energy balance, which can evolve with climate change, said Dong Wu, a scientist at NASA's Goddard Space Flight Center leading the SWIRP effort.

Wu and his team are building the instrument and planning to demonstrate SWIRP on a high-altitude balloon or aircraft next year. Once proven, the shoebox-sized instrument would be ready to fly on a satellite mission, Wu said.

SWIRP follows another instrument, also led by Wu, called IceCube. During its 15-month sojourn aboard a 3U CubeSat, IceCube produced the world's first map of the global distribution of atmospheric ice. It obtained this data in only one frequency band — 883-Gigahertz — while SWIRP will study the same phenomenon in multiple frequencies, ranging from the submillimeter or microwaves that fall between radio and longwave infrared on the electromagnetic spectrum.

Understanding ice clouds is important for interpreting Earth's radiation budget. Clouds determine how much sunlight gets in and how much gets bounced back into space. Clouds that sit at a lower altitude tend to reflect sunlight, while colder, higher-altitude clouds let more sunlight in and create a greenhouse effect. Scientists struggle to understand the impact of cirrus clouds because it's difficult to calculate how their plentiful and irregularly shaped ice crystals scatter sunlight.

SWIRP could help answer that question. SWIRP would allow scientists to see ice clouds more clearly because it measures ice clouds in three different wavelengths — the 680-Gigahertz, 240-Gigahertz and infrared bands — which are sensitive to differently sized particles.

Although existing sensors can observe small and very large ice particles, SWIRP can see intermediate ice particles, which closes an existing gap in NASA's observational capabilities. "Ice clouds are currently a knob you can adjust in climate models to make sure everything else fits," Wu added.

SWIRP will also enhance the international capabilities of cloud-ice observations. The Ice Cloud Imager, or ICI, now being developed by the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT), is a millimeter/submillimeter wave radiometer that will also measure ice clouds to support long-term climate monitoring and validate the characteristics of ice clouds in weather and climate models.

ICI is much larger than SWIRP. Not only could it be built for less money, SWIRP would enable multi-point cloud observations from a constellation of SmallSats, which would provide complete daily coverage, Wu said.

◄ A 3-D printed model of SWIRP.
Credit: Paul Padgett / NASA

Mapping Biodiversity

A new interactive map helps predict where species will move in a warmer climate.

A new ESTO-funded technology helps predict when and where pileated woodpeckers, desert pocket mice and white fir trees, among many species, could migrate under future climate scenarios.

Researchers at Duke University in Durham, North Carolina, created an interactive web portal that pulls together satellite, airborne and ground-based information, as well as climate projections and ecological forecasts, to determine how one species could impact another as they relocate and compete for suitable habitats.

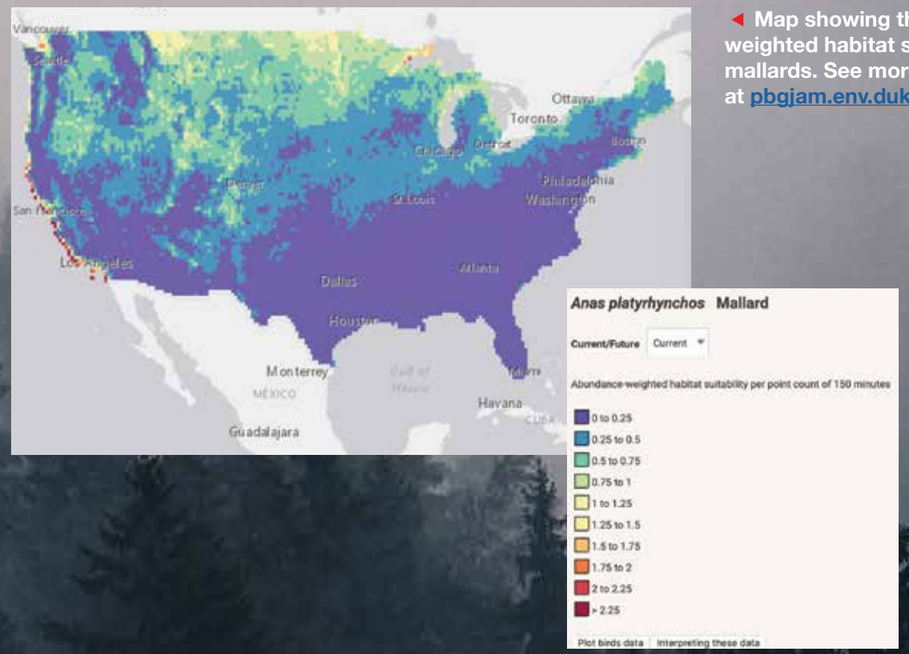
"We need to consider who's living with whom in order to understand larger impacts," said Jennifer Swenson, the project's principal investigator and a professor at Duke.

The portal, dubbed, Predicting Biodiversity with a Generalized Joint Attribution Model, or PBGJAM, aims to explore how a biodiverse community responds to climate change as a whole to more accurately predict the impact of both the individual species and the entire ecosystem.

To tackle this, the PBGJAM team built on their powerful Generalized Joint Attribution Model, or the latter part of the acronym, which can pull in different kinds of data for multiple species. For instance, the desert pocket mouse and other mice species are currently concentrated in the southwestern region of the U.S. As they start losing viable habitats with climate change, they'll be forced to move north or east, all while competing with each other for resources and scurrying from new and old predators.

The model considers how many species live in a specific region, how many suitable habitats exist for specific species, how all this could change in the future and how one species' movements could affect another's.

Adding the PB to the GJAM makes the approach easier to use for a larger audience, Adam Wilson, a professor at the University at Buffalo, said. PBGJAM provides a web interface that lowers the barrier of entry for decision makers, scientists and any interested individual to get involved. They only need to choose an ecosystem type and then see how it's shifted, Wilson said.



◀ Map showing the abundance-weighted habitat suitability for mallards. See more species layers at pbgjam.env.duke.edu/web-map.

Shining a New Light On Sun Measurements

Two CubeSat missions – the Compact Spectral Irradiance Monitor (CSIM) and the upcoming Compact Total Irradiance Monitor (CTIM) – are changing the way scientists look at the sun.

Small variations in the sun's solar energy output can have large effects here on Earth, which is why scientists have measured solar irradiance from space for 40 years. This reliable, unbroken record is critical to our understanding of the Sun and its effects on our climate, and two new CubeSats may represent a smaller, more affordable future for the continued measurement of solar irradiance.

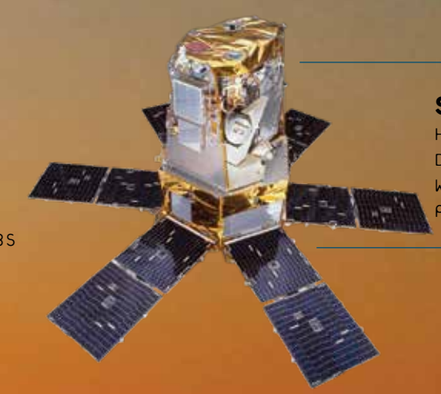
Currently, NASA has two instruments measuring solar irradiance: the SOlar Radiation and Climate Experiment (SORCE) and the Total and Spectral Solar Irradiance Sensor (TSIS-1). Both of these missions use separate instruments to measure total solar irradiance (TSI) and solar spectral irradiance (SSI). The first, TSI, is used to quantify the tiny variations in the total amount of solar energy striking the earth. SSI is a measure of the distribution of the Sun's energy across the spectrum, an important measurement because different wavelengths are absorbed by different parts of the atmosphere.

Developed by Principal Investigator Erik Richard at the Laboratory for Atmospheric and Space Physics (LASP), the CSIM CubeSat marks a significant departure from previous solar irradiance instruments. CSIM was launched in December 2018 on Spaceflight's SmallSat Express, and by early March 2019, it had obtained first-light results across its full scanning range with impressive accuracy. Although it only contributes the SSI half of the solar irradiance question, CSIM represents a significant technological advance in instrument size, weight, power and cost (SWaP-C) reductions – down to 1/10th the mass, 1/20th the volume, and 1/4th the power requirements of existing instruments – all with a potential increased accuracy.

To compliment CSIM, David Harber at LASP is building the Compact Total Irradiance Monitor (CTIM), a CubeSat demonstration mission that aims to launch in early 2021. CTIM will provide TSI measurements with accuracy and stability comparable to the current missions, while making reductions in size and weight. Together, the reduced SWaP-C of both CSIM and CTIM could translate into faster builds, cheaper launches, and ultimately, greater redundancy for future solar irradiance measurements.

CSIM
Height: 1'
Length: 8"
Width: 4"
Weight: 22 lbs
Power: 8 W

TSIS-1
Height: 8'
Length: 4'
Width: 4'
Weight: 800 lbs
Power: 32 W



SORCE
Height: 5'2"
Diameter: 3'9.5"
Weight: 640 lbs
Power: 348 W

Looking for Freshwater in All the Snowy Places

A new simulator finds the best way to measure snow from space.

Snowflakes that cover mountains or linger under tree canopies are a vital freshwater resource for over a billion people around the world. To help determine how much freshwater is stored in snow, a team of ESTO-funded researchers is creating a computer-based tool that simulates the best way to detect snow and measure its water content from space.

Snow's water content, or snow water equivalent (SWE) is a "holy grail for many hydrologists," said Bart Forman, the project's principal investigator and a professor with the University of Maryland, College Park. When snow melts, the ensuing puddle of water is its SWE.

In western U.S. states, snow is the main source of drinking water, and water from snow is a major contributor to hydroelectric power generation and agriculture.

"We would love to have a global map of SWE," said Edward Kim, a research scientist at NASA's Goddard Space Flight Center in Greenbelt, Maryland. However, there is no single technique that can measure SWE globally because snow properties vary depending on where it lands, Kim said. It often forms a deeper layer in forests, where it is sheltered from the Sun, but keeps a shallower profile in the tundra and prairie, where it is exposed to wind and higher temperatures.

Snow changes its shape as it falls to the surface and then continues to change in its resting place. Its shape can determine which sensor is able to observe it, Kim said, adding another complexity to estimated SWE.

Forman and his team's new tool evaluates three different types of Earth-orbiting sensors, radar, radiometer, and lidar, to determine the most effective combination of satellite-based sensors to produce the most data. "The tool will show us how to make intelligent choices about how to combine sensors," Kim said.

Once the data from the different sensors are in the simulation tool, the team is able to run experiments that include different scenarios, such as putting a satellite into one orbit versus another or having a satellite look at a wide swath versus narrow swath of Earth. With this suite of experiments, they can compare how well a certain combination performs compared to a benchmark scenario, Forman said.

The new snow-sensing simulation tool will help create a space-based snow observation strategy to better understand this vital freshwater resource. The simulator will be used to "continue to ask questions of what should be next and how we should be planning in 20 years or more," Forman said.

Credit: Paul Padgett / NASA

Multi-Angle Stratospheric Aerosol Radiometer

An ESTO-funded team built a miniaturized instrument to measure atmospheric aerosols that can adversely affect human health and the climate.

The team building the Multi-Angle Stratospheric Aerosol Radiometer (MASTAR) wants to fly it aboard a constellation of small, relatively inexpensive CubeSats to gather simultaneous, multi-point measurements of aerosols, which can be found in the air over oceans, deserts, mountains, forests, ice and every ecosystem in between.

"Knowing where [aerosols are] going is important economically. Measurements from a single spot on the ground won't give you the information you need," said Matt DeLand, a scientist with Science Systems and Applications, Inc., who is leading the team developing MASTAR at NASA's Goddard Space Flight Center. "Flying these instruments on multiple spacecraft would give us the global measurements we need."

Despite their small size, aerosols have major impacts, both bad and good, on Earth's climate and human health.

About 90 percent of aerosols have natural origins. Volcanoes and forest fires inject huge quantities of ash and partially burned organic carbon, respectively, into the air. The remaining 10 percent of aerosols comes from automobiles, incinerators, smelters and power plants, as well as from deforestation, overgrazing, drought and excessive irrigation. Collectively, they create the pollution and poor air quality that are particularly harmful to those with respiratory diseases.

Although aerosols can adversely affect human health and commercial enterprises at lower altitudes, they do offer a benefit at higher altitudes. They reflect sunlight back into space, essentially throwing a cooling blanket over the planet. This offsets some of the global warming caused by increasing greenhouse gases that trap heat at the surface.

MASTAR was inspired by the Ozone Mapping and Profiling Suite (OMPS) Limb Profiler, one of three instruments making up a suite of instruments flying on the Suomi NPP spacecraft, a joint mission between NASA and the National Oceanic and Atmospheric Administration (NOAA). Launched in 2011, Suomi NPP is the forerunner of a next-generation Earth-observing system designed to study long-term climate change.

MASTAR offers two distinct advantages over its larger next-of-kin: its multiple viewing angles, which would give scientists a more comprehensive accounting of the type and distribution of aerosols in the stratosphere as viewed along Earth's horizon; and its small size, ideal for flying on a tiny CubeSat platform, DeLand said.

DeLand and his team had to shrink the instrument's size to fit on a 3U CubeSat, which measures roughly 4 inches (10.16 cm) on a side and 1 foot (30.48 cm) in length. With additional ESTO support, the team is developing housing and cold-resistant software to operate the instrument in a near-space environment during the balloon flight.

DeLand believes MASTAR could eventually be used for other scientific investigations, too. "With a slight modification to the instrument, we could measure water vapor and other properties," he said. "There is more than one application for this instrument."

Specs

size (l x w x h)	16cm x 16cm x 33cm
weight	7kg
input voltage	115v AC
current	5A [nominal]
detector	Andor iKon-M 934, 1024x1024 pixels
wavelength selection	Aerosols- 670nm, 850nm (10nm bandpass) Attitude knowledge- 350nm (10nm bandpasss)
slit field of view	2.0° vertical x 0.1°vertical
altitude coverage	0-60km
altitude sample	0.38 km/pixel
data collection rate	2.0MB image / 40 seconds

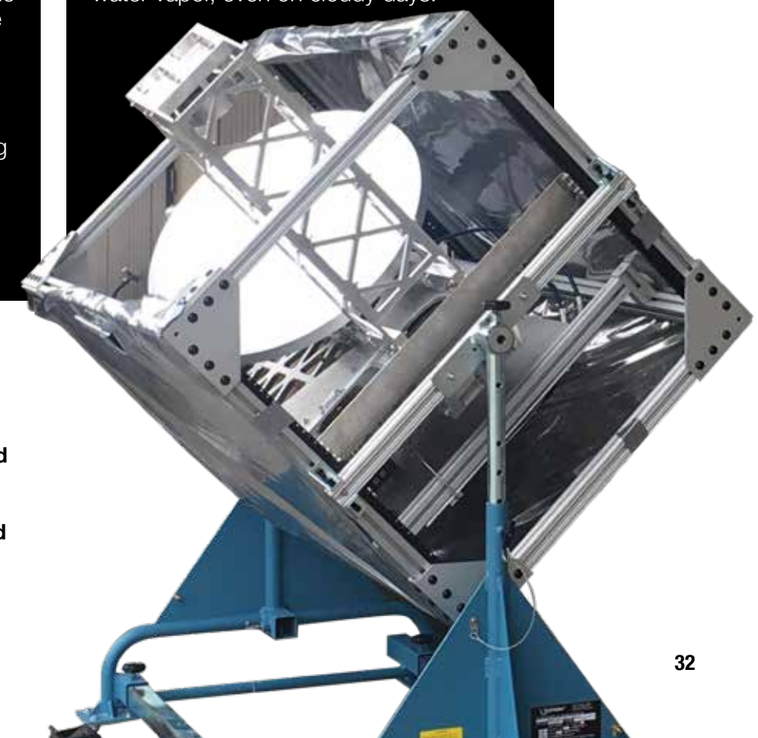
Seeing Water in the Clouds

The water vapor in Earth's atmosphere drives weather and, as a primary greenhouse gas that traps more heat than carbon dioxide, is a critical component of the climate system. As it moves around the globe, water vapor transports heat from the tropics through the mid latitudes to the polar regions, bringing rainfall and moderating temperatures. Water vapor in the atmosphere has long been measured by infrared and microwave radiometers in space and on the ground. The microwave radiometers are tuned near 183 GHz, a spectral region with a strong water vapor absorption line. But these instruments have trouble when clouds drift into view and bias their measurements.

The Vapor In-Cloud Profiling Radar (VIPR) is an emerging instrument that is attempting to tackle this problem. VIPR also uses the 183 GHz line, but unlike the radiometers, it actively emits microwaves to accurately observe inside of clouds using a differential absorption technique – it measures radar backscatter both near the peak and at a second wavelength of lower absorption to calculate the water vapor content of the clouds. In other words, VIPR can see inside and through any clouds that happen to be in the way.

Developed at the Jet Propulsion Laboratory, VIPR has undergone several ground demonstrations this year beginning with 'first light' testing in October 2018. In December 2018, VIPR took several hours of observations at the Center for Western Weather and Water Extremes at the Scripps Institution of Oceanography, and the data were compared to radiosonde measurements. Then, in April 2019, VIPR was deployed to the Department of Energy's Atmospheric Radiation Measurement facility in Oklahoma, where the VIPR team spent two weeks carefully calibrating measurements against radiosondes and other humidity instruments. The VIPR data from these tests revealed profiles of water vapor in clouds derived to less than 10% uncertainty, which compares favorably to the roughly 20% uncertainty of currently-operational instruments in clear sky conditions.

In early 2020, the VIPR team is preparing to take the instrument airborne aboard a Twin Otter aircraft. The roughly 30 hours of flights will take place over the Pacific Northwest, taking full advantage of the ever-present cloud cover. The flights will also help the team tease out the reflective effects of a variety of ground surfaces – forested land, urban areas, the ocean, etc – on VIPR data. If all goes well, VIPR could soon be put into regular service measuring water vapor, even on cloudy days.



▶ During the December 2018 field tests at Scripps, VIPR observed six hours of a cold front passage, and measurements were validated against eight radiosondes. Credit: Matthew Lebsock, JPL

A Coordinated Dance in Outer Space

New software helps plan future Earth observing mission operations.

As Typhoon Trami churned across the Pacific Ocean, bringing fierce winds and rain to Japan and Taiwan in September 2018, two shoebox-sized satellites happened to peer down at it at the same time, their instruments recording how the storm was forming and changing.

Combining data on the typhoon from the CubeSats TEMPEST-D and RainCube created a more complete picture of the storm. Although the coordination was fortuitous in this case, a new NASA-funded technology led by researchers at The Ohio State University (OSU) in Columbus, Ohio could help plan future joint observations.

Researchers at OSU have created a software library that is able to simulate how future adaptive sensors, which can perceive and react to their surroundings, on CubeSats and other satellites will communicate with each other to coordinate how best to image Earth.

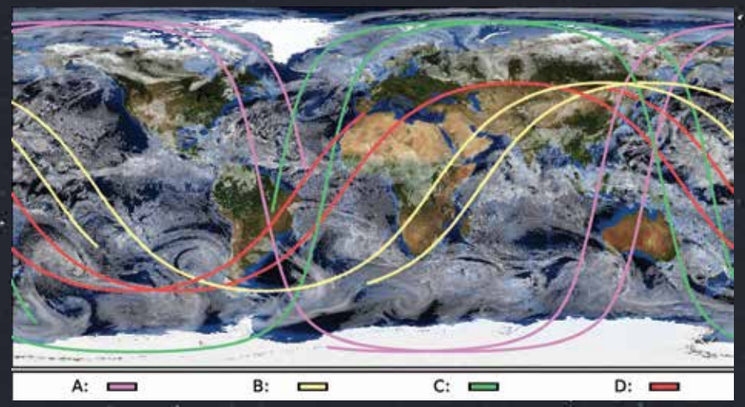
"This project aims to expand existing software tools for planning Earth observing missions so that they can simulate adaptive sensors that collaborate and the resource constraints associated with CubeSat platforms," said Joel Johnson, the project's principal investigator and a professor at OSU.

Johnson and his team call the new suite of software STARS, short for Simulation Toolset for Adaptive Remote Sensing. STARS consists of three distinct components that can be used separately or in combination. Each component helps to answer the following questions: 1) Should a sensor take a measurement? 2) Which sensor on which satellite should take it? 3) How should the sensor take a measurement?

In addition to being able to use these tools individually or in combination, users are also able to customize their simulations with whatever inputs they want. "We're aiming for a fill-in-the-blank structure that makes it easy for users to adopt the library," said Graeme Smith, a co-investigator and research assistant professor at OSU.

"We want to advance the adoption of these technologies to improve the Earth observing system," Johnson said.

▼ The image below shows a STARS simulation of the orbits of four satellites (A, B, C and D) involved in a coordinated observation. The satellites are in distinct orbit planes so they rely on dynamic planning of multi-hop communication links to ensure they can queue other instruments to take high-priority measurements. Credit: Joel Johnson, OSU



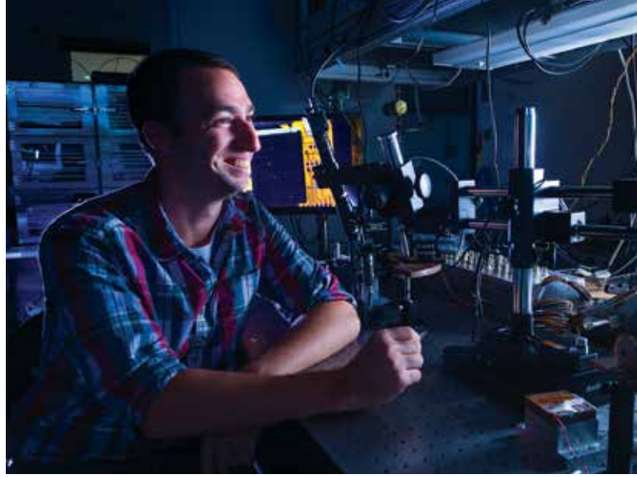
As with many research and development projects, students are integral to the work and success of technology development teams. Since ESTO's founding, nearly 900 (878 actual) students from 149 institutions have worked on various ESTO-funded projects. Aided by their experiences, these students have often gone on to work in the aerospace industry and in related fields.

In FY19 alone, nearly 100 students (98 actual, from 37 institutions, in 20 projects) were involved with active ESTO projects. Most typically, these students are pursuing undergraduate and graduate degrees, but occasionally high school students also join in on the technology development work.

Student Participation

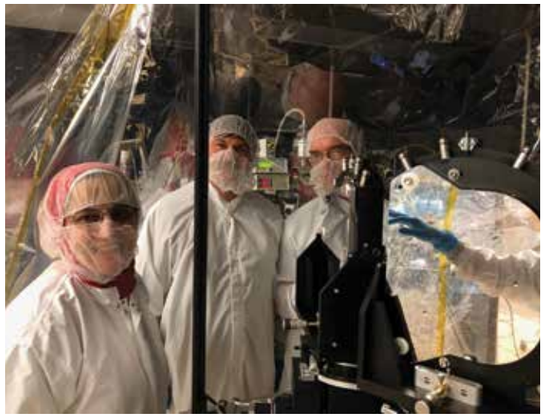
Caitlyn Cooke (below at left) works as a microwave design engineer for Northrup Grumman Corporation and is pursuing a Ph.D. in electrical engineering at the University of Colorado, Boulder. At Northrop Grumman, she is responsible for the integration and testing of a new receiver intended for the SWIRP (Sub-millimeter-Wave and long-wave-InfraRed Polarimeters) instrument being built at the NASA Goddard Space Flight Center by Principal Investigator Dong Wu (see page 21). SWIRP could enable improved measurements of cloud ice, a major source of uncertainty in climate models. In this photo from 2015, Caitlyn also had the opportunity to fly on the NASA DC-8 aircraft during the Olympic Mountain Experiment (OLYMPEX) airborne science campaign, an effort that collected detailed atmospheric measurements to evaluate how well rain-observing satellites measure rainfall and snowfall from space. Credit: Jeremy Dwyer-Lindgren / USA TODAY

Matt Laffin (above) is pursuing a Ph.D. in Earth System Science at the University of California, Irvine, and works on the Justified Automated Weather Station (JAWS) project led by Charlie Zender (see page 15). JAWS is a system that automatically converts and formats the data from far-flung weather stations in remote corners of Antarctica and Greenland. When he's not hiking with his dog Henry, Matt uses the JAWS data to study Antarctic surface melt climatology caused by foehn winds – the strong, warm winds that blow down from higher elevations.
Credit: Matt Laffin



A Ph.D. student at the Integrated Photonics Laboratory at the University of California, Santa Barbara (UCSB), **Joseph Fridlander** (right) is conducting research to develop phase-locked photonic integrated circuits for the IMPRESS Lidar project (Integrated Micro-photonics for Remote Earth Science Sensing Lidar) led by Jonathan Klamkin at UCSB. The effort is developing an extremely small, high-precision lidar instrument to measure CO_2 from space – and potentially other atmospheric constituents as well. Joseph spent nearly three years as a radio frequency engineer at the Jet Propulsion Laboratory before embarking on doctoral studies.
Credit: Matt Perko / UCSB

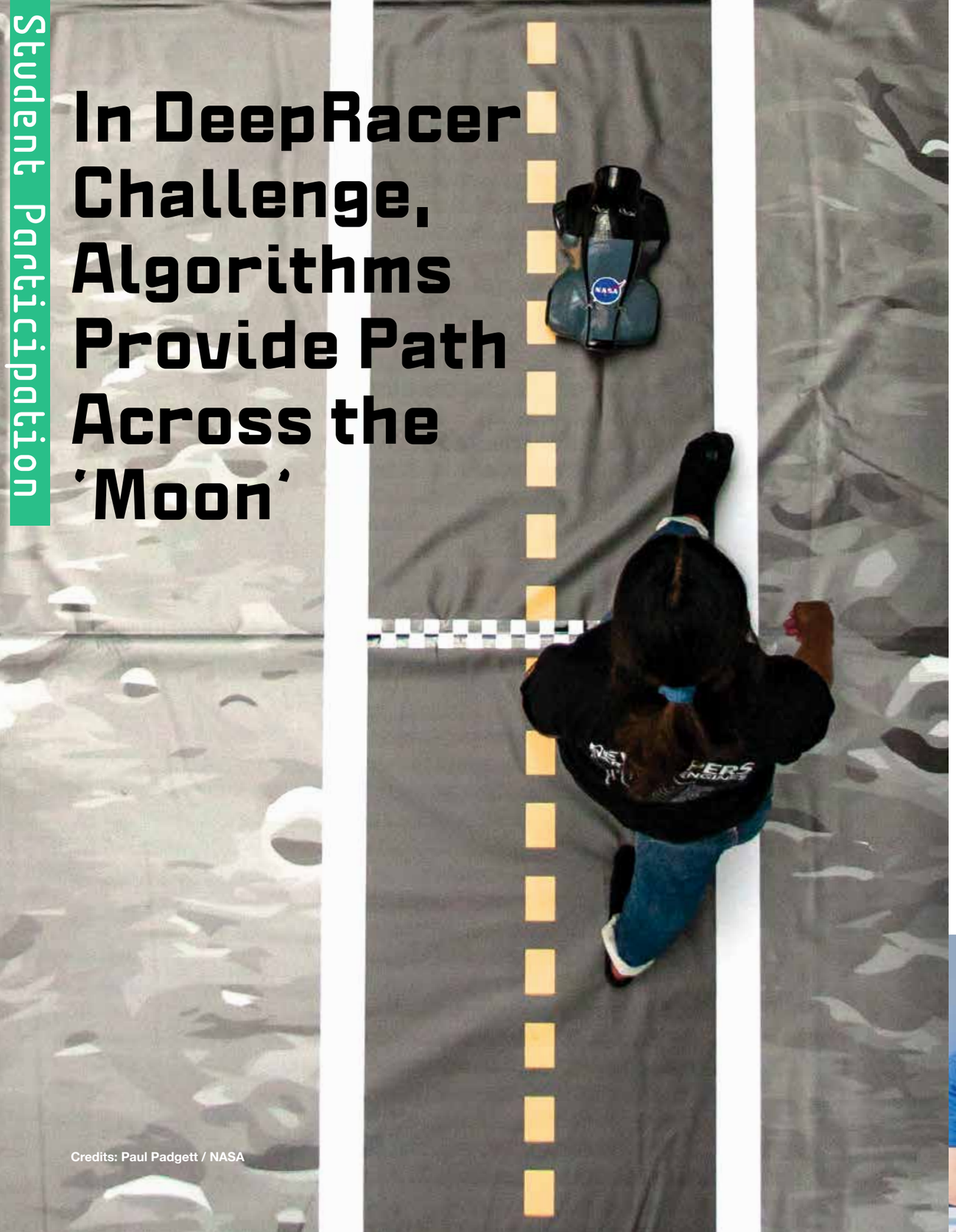
When **Pardhasai Chadalavada** closes his eyes he sees satellite orbits. Specifically, he sees miniature radar satellites called RainCube CubeSats hurtling around the Earth, tracking hurricanes in real-time. Today only one RainCube satellite exists in space – a technology demonstration mission which has taken numerous measurements of hurricanes and tropical storms over the last year. But Pardhasai is working toward a more ambitious vision. "Basically the idea is to design a constellation of RainCubes so that we can monitor hurricanes continuously," he says. Now in his third year of doctoral studies in at Wichita State University, Pardhasai received a grant from ESTO through NASA's Future Investigators in NASA Earth and Space Science and Technology (FINESST) program. Alongside his advisor, Atri Dutta, an aerospace engineering professor at Wichita State, Pardhasai is investigating all the variables – orbit angles, swath, constellation size, networks, and autonomous operation – that might maximize the utility of such a constellation and provide the most observations over areas where hurricanes develop.
Credit: Kayla Deines / Wichita State University



In May 2019, **Manal Khreishi** (left) received her Ph.D. in Optical Sciences at the University of Arizona. Over the last year Manal also interned at the NASA Goddard Space Flight Center, working with ESTO Principal Investigator Jon Ranson (center) on the MiniSpec instrument (at far right), a miniaturized imaging spectrometer intended to measure reflected sunlight to monitor vegetation health, carbon, water, and the energy cycle. Her work focused on new ways to measure and align the precision optics to construct a working spectrograph. Now a full-fledged NASA civil servant at Goddard, Manal is embarking on the end-to-end testing of MiniSpec to demonstrate its spectral performance.
Credit: Raymond Ohl / NASA

Student Participation

In DeepRacer Challenge, Algorithms Provide Path Across the 'Moon'



Credits: Paul Padgett / NASA

On a vinyl race car track resembling the surface of the Moon, summer interns took turns racing a toaster-sized autonomous car. Their goal? To see whose algorithm could propel the car the fastest while staying on the track.

The shoe-shaped track for the NASA DeepRacer Challenge – which took place on Aug. 8 at NASA Goddard Space Flight Center – required participants to come up with an algorithm that would steer the vehicle as it approached both left and right turns, as well as straightaways.

"Nice, that's a good turn!" said a representative from Amazon Web Services (AWS), which developed the DeepRacer autonomous cars, as intern Akshay Anil watched the race car run on his algorithmic model, dubbed "Lil'Carty A."

The event's ultimate purpose was to provide a fun, engaging way to demonstrate how machine learning works. Prior to the big race, interns attended a workshop with representatives from AWS to learn how to program a model and guide the car as it attempts to complete laps around a racecourse.

Models relied on reinforcement learning, meaning they would be rewarded when they followed the track and penalized when they strayed off course. These same principles can help in real scientific endeavors, like guiding a future planetary rover as it attempts to navigate new terrains.

"I hope that this project will spark more interest in reinforcement learning as a means to produce cost-effective methods for automating tasks that need to be done," Anil said. He hopes to become a software engineer when he graduates with a computer science degree from the University of Maryland, College Park.

Fellow competitor and intern Emma Zimmerman is also studying computer science at Seattle Pacific University. "I'm in a club for women in engineering and computer science, and I would absolutely love to get them involved in things like this," she said. She named her model "Tracy Chapman" in reference to the singer's song "Fast Car." "One of the most valuable parts of my experience with the race is being able to bring my knowledge back to others," Zimmerman said.

National Aeronautics and Space Administration

Earth Science Technology Office
NASA GSFC, Code 407.0
Greenbelt, MD 20771

www.esto.nasa.gov