Earth Science Technology Office

National Aeronautics and Space Administration

Annual Report 2021

Executive Summary

As you'll read in the pages that follow, 2021 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.

For the second year in a row, the Earth Science Technology Forum (ESTF2021) was held virtually due to COVID-19 restrictions. We were pleased to have Dr. Karen St. Germain, Director for Earth Science at NASA, kick off the eight ESTF2021 sessions, held late May through early July.

In fiscal year 2021 (FY21), ESTO continued to build upon its 24-year heritage of technology development. This year, 39% of active ESTO technology projects advanced at least one Technology Readiness Level (TRL), and as many as 20 active and completed projects were transitioned to follow-on development efforts or infused into Earth observing missions, operations, or commercial applications. We are particularly proud to report that at least 104 students – high school through PhD – were directly involved in ESTO-funded projects this year.

New projects were added through competitive solicitations under the Advanced Component Technology (ACT) and the In-Space Validation of Earth Science Technologies (InVEST) program elements, in December 2020 and June 2021 respectively. And as of publication, three program elements – the Instrument Incubator Program (IIP), the Advanced Information Systems Technology (AIST) program, and the Decadal Survey Incubation (DSI) program – expect to announce new awards in early FY 2022. We welcome these new cohorts of technologists and look forward to the contributions they will make.

Finally, it is with great sadness that we note the sudden passing of our colleague, Dr. Gail Skofronick-Jackson, in September. Gail was a brilliant scientist and served as a Weather and Atmospheric Dynamics Program Manager within the NASA Earth Science Division, where she was a consistent champion for technology development. She also worked closely with ESTO on many efforts, including as Program Scientist for the Planetary Boundary Layer observable through the Decadal Survey Incubation program. For all who wish to memorialize Gail, a scholarship for science and electrical engineering students has been established in her name at Florida State University (learn more: spark.fsu.edu/GailSkofronickJackson).

Pamela S. Millar
Program Director

Robert A. Bauer
Deputy Program Director

ABOUT ESTO

As the technology development function within NASA's Earth Science Division, the Earth Science Technology Office (ESTO) 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 select the best cutting-edge technologies, from advanced sensors aboard miniature satellites to software tools that plan new observations and harmonize, fuse, and analyze large data sets from various sources.

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

Table of Contents

2021 Metrics

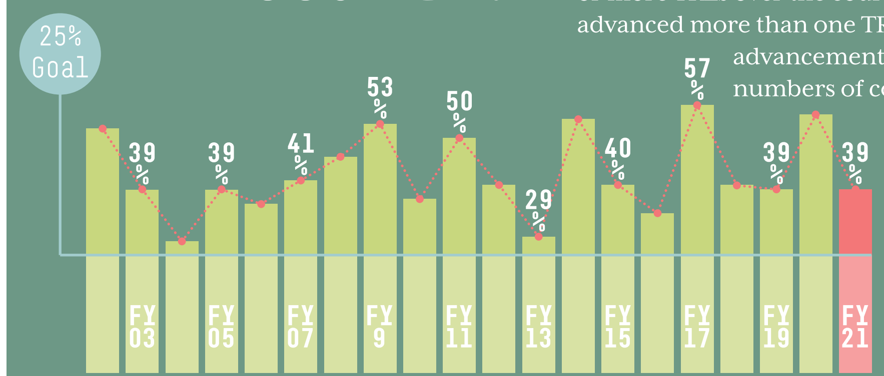
With over 1,000 technology investments made since 1999 and an active portfolio of 136 projects during FY21 (October 1, 2020, through September 30, 2021), ESTO drives innovation, enables future Earth science measurements, and strengthens NASA's reputation for developing and advancing leading-edge technologies. To clarify ESTO's FY21 achievements, what follows are the year's results tied to our performance metrics.

GOAL 1 :

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

FY21 Result :

39% of ESTO technology projects funded during FY21 advanced one or more TRLs over the course of the fiscal year. Eight 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 42%.



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

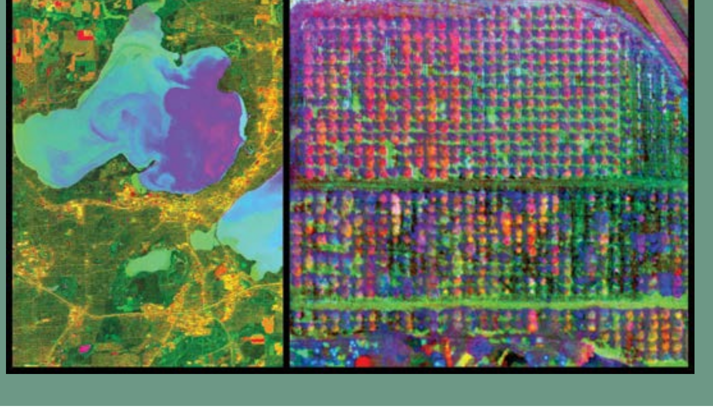
GOAL 2 :

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

FY21 Result :

In this fiscal year, at least 8 ESTO projects achieved infusion into science measurements, airborne campaigns, data systems, or follow-on development activities. Three notable examples follow.

Project Highlights :



EcoSML

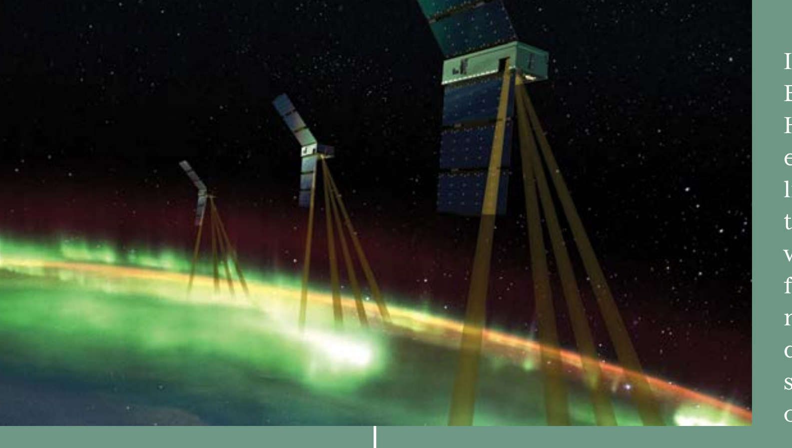
The Ecological Spectral Model Library (EcoSML) is one of several tools developed under the Ecological Spectral Information System, a 2016 Advanced Information Systems Technology project (PI: Phil Townsend, University of Wisconsin). EcoSML has been added to GitHub, a cloud-based service that helps developers store and manage their code, enabling researchers to share models and facilitating the use of spectral data by the larger scientific community.

GOAL 2 : Project Highlights :

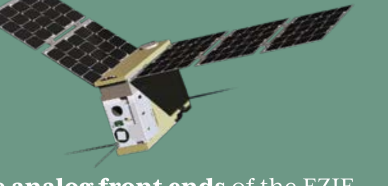
UWBRAD

The Ultra WideBand software defined microwave RADiometer (UWBRAD) instrument developed under the 2013 Instrument Incubator Program solicitation was deployed with support from the National Science Foundation as part of the international Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) expedition. MOSAiC was conducted to investigate the Arctic processes and evolution of ocean-ice-atmosphere system in the polar region.

EZIE Infusions



In late 2020, the Electrojet Zeeman Imaging Explorer (EZIE) mission was selected by NASA's Heliophysics Science Division to explore electric currents in Earth's atmosphere that link the aurora to the magnetosphere. Led by the Johns Hopkins Applied Physics Lab, EZIE will be comprised of three CubeSats flying in formation and carrying payloads containing millimeter radiometers with high-resolution digital spectrometers. These payloads include substantial heritage from technologies originally developed through ESTO:



The analog front ends of the EZIE radiometers are derived directly from the TEMPEST-D (TEMPoral Experiment for Storms and Tropical systems–Demonstration, PI: Steven Reising, Colorado State) CubeSat, an Earth Venture Instrument launched in May 2018 to demonstrate observations of cloud and precipitation processes.

The digital back ends were developed for use on the CubeRRT (CubeSat Radio Frequency Interference Radiometer Technology, PI: Joel Johnson, Ohio State) CubeSat, which also launched in May 2018 and demonstrated on-board, real-time Radio Frequency Interference (RFI) processing from space.

The overall digital design is based on early work on an Agile Digital Detector by Chris Ruf at the University of Michigan (who is also serving as the EZIE Deputy Project Scientist), through a 2004 award under the Instrument Incubator Program that has enjoyed widespread infusion, including by the Hurricane Imaging Radiometer (HIRAD) airborne instrument.

GOAL 3 :

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

FY21 Result :

Several projects satisfied this goal in FY21. One notable example follows:

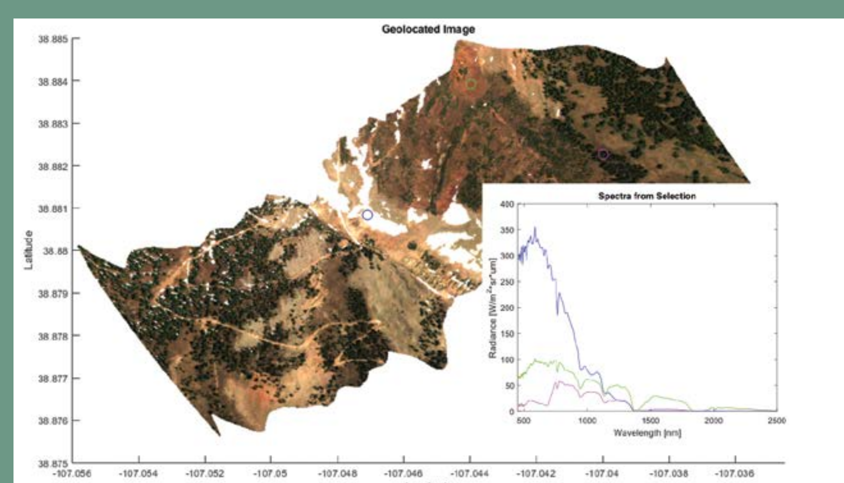
Compact Hyperspectral Prism Spectrometer

The Compact Hyperspectral Prism Spectrometer (CHPS), a new instrument developed at Ball Aerospace (Principal Investigator: Thomas Kampe), was put through a series of test flights in 2019 and 2020 aboard a Twin Otter aircraft in order to demonstrate the technology for future Landsat missions. The compact spectrometer could help maintain Landsat's legacy of accurate and stable calibration – key to developing new hyperspectral approaches for a broad range of science investigations, from surface ecology and biodiversity studies to water quality monitoring and land use analysis.

CHPS features low stray light and low polarization sensitivity, improvements made possible by careful instrument design and the use of a prism in place of gratings. A new broadband anti-reflection coating applied to the prism elements helps to minimize transmission losses and reflections, and the CHPS team developed a novel prism alignment method. As a result, a spaceborne version of CHPS is small enough to be launched as a secondary payload, perhaps on an ESPA Grande ring, rather than as a standalone mission

The flight tests, which totaled about 40 hours on a Twin Otter out of Grand Junction, Colorado, produced high-quality science data which was processed to Level 1B. Concepts for a spaceborne instrument, potentially aboard a future Landsat mission, were also developed and provided to NASA and USGS as part of the 2020 Architecture Study Team project.

▼ CHPS instrument integration onto a Twin Otter aircraft in Grand Junction, CO. Credits: Thomas Kampe / Ball Aerospace



▶ An example of CHPS data, taken over the USGS survey site at Crested Butte, CO. Spectral bands were combined to create the RGB image. The Level 1B CHPS data provides geolocated continuous spectra over the full 450-2300 nm band for each pixel, enabling selection of any ground location for spectral information. Inset shows spectra corresponding to the three locations noted in the image: snow (blue), soil (green), and evergreen trees (magenta).

2021 Program Updates

Decadal Survey Incubation

The newest program element managed by ESTO, Decadal Survey Incubation (DSI), seeks to accelerate the readiness of two high-priority observables needing science-requirements refinement, technology development, and/or other advancements prior to cost-effective flight implementation. As its name suggests, DSI was recommended by the National Academies in the 2017 Earth Science Decadal Survey to target the Planetary Boundary Layer (PBL) and Surface Topography and Vegetation (STV) areas. These two fields are complex and dynamic systems with important science objectives and societal applications. Advancing technology to support these areas will improve observational capabilities that may unlock new insights into a wide variety of Earth processes.

In 2020, two study teams were competitively selected to "identify methods and activities for improving the understanding of and advancing the maturity of the technologies applicable to these two targeted observables and their associated science and applications priorities." Each team produced a report that helped inform the first DSI solicitation for proposals, released in FY21. Awards are expected in FY22. For more information on DSI, the study team reports, and the solicitation, visit: https://esto.nasa.gov/incubation/.

Advanced Information Systems Technology

Advanced information systems play a leading role in the collection, processing, integration, analysis, understanding, and utilization of vast amounts of Earth science data, both in space, in situ or on the ground. Advanced computer intelligence and technology concepts that enable novel acquisition, discovery, fusion, and analytics strategies for terabytes of diverse 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. Recently, AIST has focused on the following areas:

New Observing Strategies

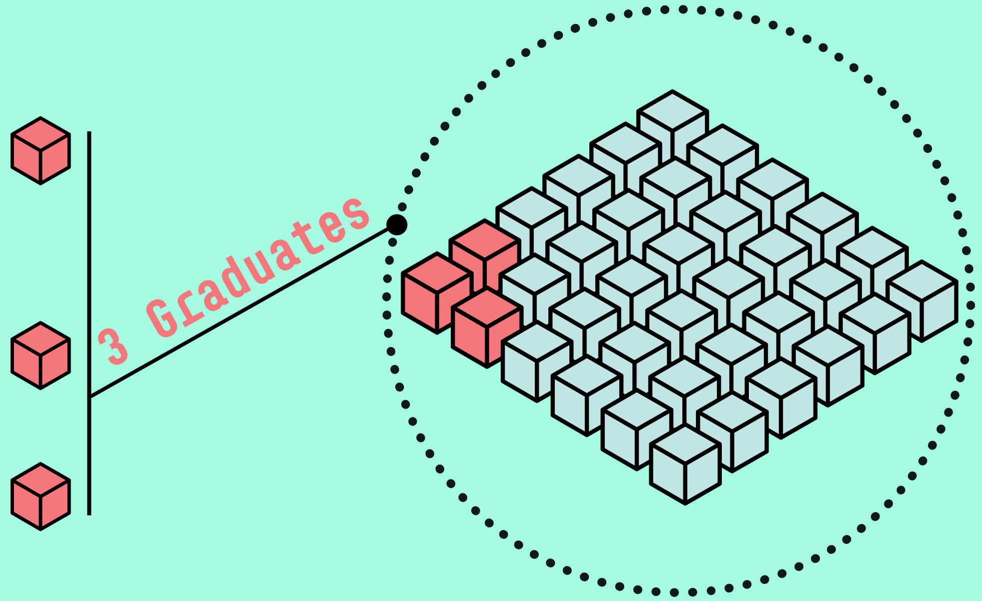
With each new Earth science measurement comes a new observing system design. This thrust helps develop and evolve new ways of designing novel Earth observation systems and capabilities to incorporate technological advances, like constellations of small satellites and smarter sensors, and information dynamically gathered from space, air, and ground-based sources. We have more observation capabilities and tools than ever before, providing researchers with an arsenal of data-collecting possibilities. This thrust aims to develop architectures that could autonomously coordinate and integrate data from sensor webs, including small satellites and UAVs. Technology advances are creating opportunities to make these new measurements and to continue others more effectively.

Analytic Collaborative Frameworks

Once Earth observing missions are in operation, very large amounts of data are collected. Data from different missions often have different formats and diverse resolutions that, when combined with ground-based and airborne-derived data, provide comprehensive information that can improve science understanding. Scientists can utilize these agile analytic frameworks, which enhance and enable focused science investigations using disparate datasets and pioneering visualization and analytics tools including machine learning as well as relevant computing environments.

In 2022, AIST will add a third focus area: **Earth System Digital Twins** – capabilities for developing integrated Earth Science frameworks that mirror the Earth with state-of-the-art Earth system and human models and simulations, timely and relevant observations, and analytic tools, enabling the exploration of various hypothetical and predictive scenarios.

36 Projects Active in FY21



National Center for Supercomputing Applications (NCSA) Data Fusion Visualization for NASA CAMP²Ex Field Campaign – Larry Di Girolamo, University of Illinois at Urbana-Champaign

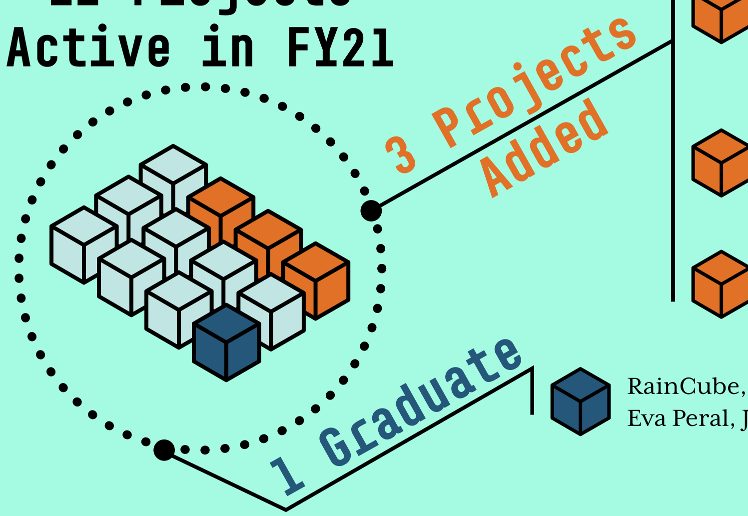
NOS Study Sensorweb integration concepts – Dan Crichton, Jet Propulsion Laboratory

Automated Smart Instrument Tasking for NASA Urgent Response – Cathleen Jones, Jet Propulsion Laboratory

In-space Validation of Earth Science Technologies

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.

12 Projects Active in FY21



The Aerosol Radiometer for Global Observation of the Stratosphere (ARGOS) Instrument – Matthew DeLand, Science Systems And Applications, Inc.

ARCSTONE: Calibration of Lunar Spectral Reflectance from Space – Constantine Lukashin, NASA Langley Research Center

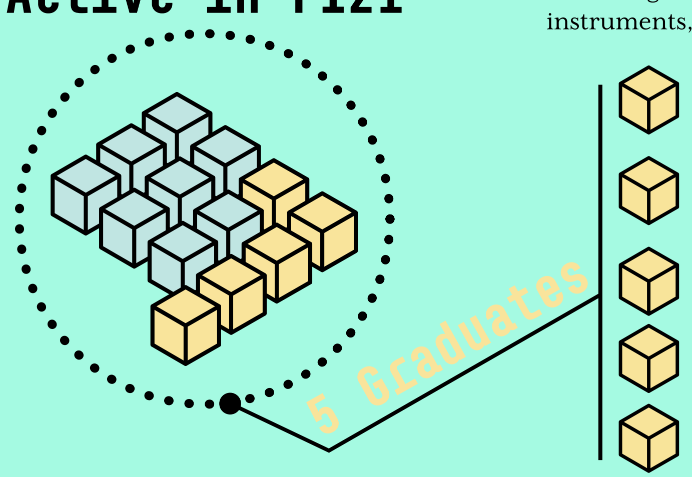
Active Cooling for Methane Earth Sensors – Charles Swenson, Utah State University

RainCube, A Precipitation Profiling Radar in a CubeSat – Eva Peral, Jet Propulsion Laboratory

Sustainable Land Imaging – Technology

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.

13 Projects Active in FY21



Long Wavelength Infrared Focal Plane Array For Land Imaging – David Ting, Jet Propulsion Laboratory

Advanced Technology Land Imaging Spectroradiometer (ATLIS) – Jeffery Puschell, Raytheon

Compact Hyperspectral Prism Spectrometer – Thomas Kampe, Ball Aerospace & Technologies Corp

Reduced Envelope Multi-Spectral Imager – Dennis Nicks, Ball Aerospace & Technologies Corp

Multi-Spectral, Low-Mass, High-Resolution Integrated Photonic Land Imaging Technology – Ben Yoo, University of California, Davis

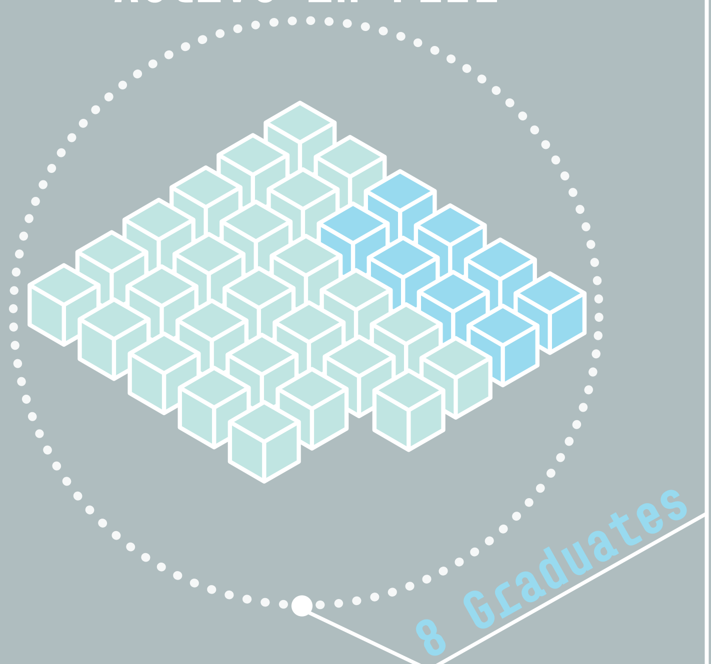
Observation Tech

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 two main programs: the Instrument Incubator Program, and Advanced Component Technologies.

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.

34 Projects Active in FY21

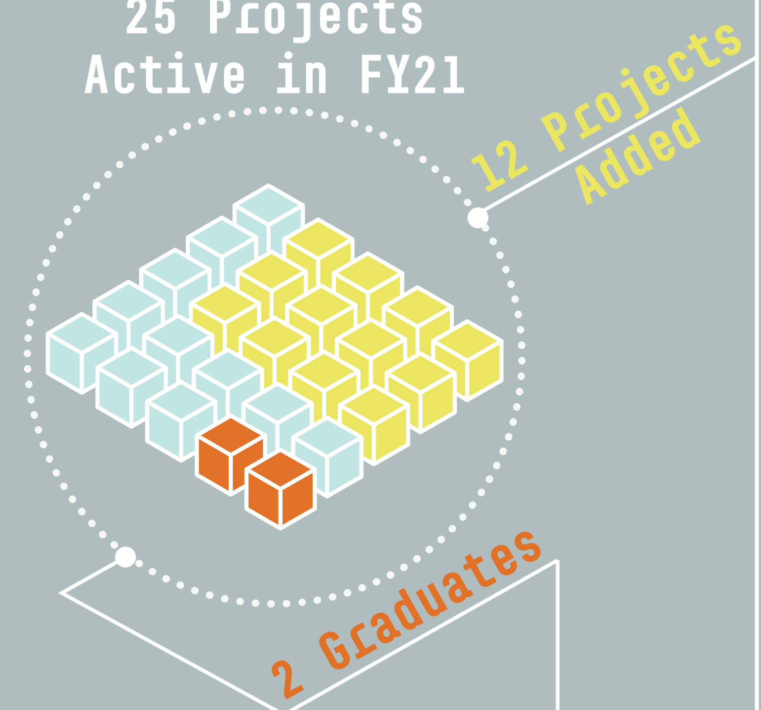


- Wideband Autocorrelation Radiometer Receiver Development and Demonstration for Direct Measurement of Terrestrial Snow and Ice Accumulation– Roger De Roo, University of Michigan
- Next Generation GNSS Bistatic Radar Receiver – Chris Ruf, University of Michigan
- ARCSTONE: Calibration of Lunar Spectral Reflectance from Space – Constantine Lukashin, NASA Langley Research Center
- Compact Midwave Imaging System- Michael Kelly, Johns Hopkins University Applied Physics Laboratory
- Advanced Development of a Multi-Angle Stratospheric Aerosol Radiometer (MASTAR) – Matthew DeLand, SSAI
- Multi-Band Radiometric Imager Utilizing Uncooled Microbolometer Arrays with Piezo Backscan for Earth Observation Mission Applications – Philip Ely, Leonardo DRS
- 3-D Global Winds: A high pulse rate, lower technology risk coherent wind lidar for airborne science and a global winds pathfinder mission – Michael Kavaya, NASA Langley Research Center
- Stratospheric Aerosol and Gas Experiment (SAGE) IV Pathfinder – Robert Damadeo, NASA Langley Research Center

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.

25 Projects Active in FY21



- Carbon Absolute Electrical Substitution Radiometers (CAESR) – David Harber, University of Colorado LASP
- P/I band multi-frequency reflectometry antenna for a U-class constellation - James Garrison, Purdue University

- W-Band RF-Photonics Receiver for Compact Cloud and Precipitation Radars – Razi Ahmed, Jet Propulsion Laboratory
- Photonic Lantern Interferometric Receiver for Remote Sensing Applications – Rodrigo Amezcua Correa, University of Central Florida
- Advancing the Radio Frequency Payload for a 3-D Lightning Geolocation Capability with a Constellation of CubeSats – Sonja Behnke, Los Alamos National Lab
- A Compact, High-Power 167-174.8 GHz Traveling-Wave Tube Amplifier for Planetary Boundary Layer Differential Absorption Radar – Kenneth Kreischer, Northrop Grumman Systems Corporation
- Ultra-Wideband Photonic Spectrometer for PBL Sensing – Thomas Dillon, Phase Sensitive Innovations, Inc.
- Visible to SWIR Fast eAPDs for Panchromatic FTS Instrument – Arvind D'Souza, DRS Network & Imaging Systems, LLC
- Bandstructure Engineered Type-II superlattice Antimonide Avalanche Photodiodes (BETA-APD) for Space Lidar Instruments – Sanjay Krishna, Ohio State University
- Radar on a Chip – Lute Maleki, OEwaves Inc.
- Miniaturized Microwave Absolute Calibration (MiniMAC) for Sounders and Imagers on SmallSat and CubeSat Platforms – Steven Reising, Colorado State University
- Stacked Miniaturized And Radiation Tolerant Intelligent Electronics (SMARTIE) – James Yamaguchi, Irvine Sensors Corporation
- Advanced SAPHIRA HgCdTe APD Arrays for NASA Space Lidar Applications – Guangning Yang, NASA Goddard Space Flight Center
- Hyperspectral Imaging on Photonic-Integrated-Circuits for Future GeoCARB Missions – Ben Yoo, University of California, Davis

Predicting What We Breathe

Machine learning helps forecast air pollution events in Los Angeles.

Air pollution kills approximately seven million people each year according to the World Health Organization (WHO). That's a life lost every five seconds to a variety of preventable cancers, infections, and other illnesses afflicting communities struggling to maintain clean air.

"Those deaths are tragic. Cities use lots of different strategies to try and protect people, but our mitigation strategies are limited by the amount of air quality data we have at our disposal," said Jeanne Holm, Deputy Mayor of Budget and Innovation for the City of Los Angeles.

With a grant from ESTO, Holm and a team of researchers are working on advanced machine-learning software that could make it easier for cities to forecast air pollution events. Their project, aptly titled "Predicting What We Breathe (PWWB)," combines deep neural network models with other classic machine-learning algorithms to identify relationships between air quality data gathered from ground sensors in Los Angeles and imaging data gathered from Earth-monitoring satellites managed by NASA and the U.S. Geological Survey (USGS).

Understanding these relationships would enable scientists to train systems used to process data from sources like Terra MODIS, Aqua MODIS, and Landsat to detect signs of impending air pollution incidents too subtle to be detected by in situ sensors in LA. In addition, PWWB would help researchers not only better classify urban air patterns in LA, but also allow them to detect similarities between those air patterns and other air regimes in megacities around the world. This capability would enable urban communities worldwide to protect their citizens from the harmful effects of air pollution with data-driven mitigation strategies.

"Our goal is to create a tool anyone can use to predict and prevent air pollution events. We want to empower other cities to keep their citizens safe as well," said Holm.

Los Angeles already uses an extensive network of air quality sensors to keep tabs on pollution. These sensors are in LA's ports, parks, and even streetlights, providing officials with critical information about the air their citizens breathe. If air quality is poor, the city can issue an advisory encouraging citizens to take precautions.

"Effective forecasting is one of the best ways to keep citizens healthy. It gives people who are particularly prone to respiratory illness time to connect with their healthcare provider and start preventative treatments. Being proactive is key to avoiding a health emergency," said Dawn Comer, LA's Broadband and Digital Inclusion Coordinator.

But LA's system for detecting air pollution is limited to the Los Angeles metropolitan area, and events far away from the city can have just as big an impact on air quality as traffic on Ventura Boulevard. For example, wildfires in other parts of California could jettison large amounts of particulate pollutants into LA's air and cause an unexpected spike in air pollution.

"Earth is a system of systems. If we want to effectively mitigate air pollution, we need to be able to look at the big picture and understand how our city fits within the broader environmental picture," said Holm.

To discover relationships between data gathered from ground-based air quality sensors and NASA satellite observations, PWWB will use multimodal deep learning algorithms. These algorithms include several deep Recurrent Neural Network (RNN) models, which are ideal for forecasting outcomes from time-series data. That makes them well-suited to comb a wide variety of data sources—including sensor measurements, satellite images, meteorological data, and wildfire data—to locate patterns between information from LA's sensor network and images collected by NASA and USGS. Essentially, these models teach data classifiers to identify signs of an impending air pollution event in satellite images of Earth's surface.

"Any relationship between our air quality data and Landsat images could be too nuanced for human analysts to detect, so we need to develop new information systems to find these patterns for us," said Holm.

Perhaps the most remarkable aspect of PWWB is its flexibility. Holm, who served the Obama Administration as an appointed Open Data Evangelist, says that her team will release their modeling software open-source on the popular coding site GitHub once it's complete, allowing anyone with a computer to access their work and tailor it to fit any urban environment in the world.

"Air pollution isn't just an LA problem. There are people all over the world who are struggling to stay healthy in polluted urban environments, and if others can use PWWB to mitigate air pollution more efficiently, then it can only help us all in the long run," said Holm.

Preparing PWWB for the general public is no small feat. Holm credits her team, especially her Co-Investigators at California State University, Los Angeles, and the non-profit OpenAQ, for making this project possible.

"Dr. Mohammad Pourhomayoun's team at California State University, Los Angeles, is instrumental for unraveling the complexities of normalizing satellite and ground data with varying scales of time and space, and Jeremy Taub's team at OpenAQ unites collaborators from the LA area with cities around the globe to help us apply these algorithms to real data sets collected from each of their cities," said Holm.

PWWB is still in the early phases of development, but Holm hopes to have a valid prototype algorithm ready in the near future. "There's a lot of work to be done, but using machine-learning to process data from space-based remote sensors can really change the way we forecast air pollution events," said Holm.

Up In the Clouds

A new smart instrument aims to change the way we look at ice crystals in the atmosphere.

Wispy white cirrus clouds stretched across a blue sky may seem insubstantial, but they actually have a huge impact on Earth's climate. Learning more about these clouds would allow scientists to develop better models for understanding storms and climate change.

"Cirrus clouds cover more than 50% of our planet. If we can build a better body of fundamental data describing the structure of these clouds, we'll have a far superior understanding of how that coverage will affect our weather and climate moving forward," said William Deal, a staff engineer at Northrop Grumman Systems Corporation.

Deal is working with a team of researchers at Northrop Grumman and the Jet Propulsion Laboratory (JPL) to develop a new instrument that would reduce the cost and complexity of using space-based remote sensors to study the tiny ice crystals making up cirrus clouds. Their project, Smart Ice Cloud Sensing (SMICES), combines three passive multi-band radiometers with an active millimeter-wave radar system to measure the size and shape of these ice crystals as they float through the troposphere.

In addition to gathering multi-angle data on these ice crystals, SMICES would also gather data to improve the understanding of the formation of tornadoes and hurricanes in near real-time, exploring how high-altitude ice clouds might impact the location, severity, and frequency of these storms. This information would make it easier for researchers to refine their models for forecasting severe weather events and predicting the long-term effects of climate change.

An intelligent instrument, SMICES would employ artificial intelligence algorithms to make independent decisions regarding power consumption, which would make it the first NASA sensor fit for using energy-intensive active radar systems within shoe-box-sized CubeSat platforms to collect dynamic measurements of ice clouds. "This is an incredibly compact, semi-autonomous, low-power solution for studying high-altitude ice clouds and their relationship with climate and weather trends. The data SMICES sends back to Earth will have a significant impact on global climate models," said Deal.

Cirrus clouds both alleviate and exacerbate the effects of climate change. While thick cirrus clouds packed with large ice crystals help regulate Earth's global temperature by reflecting incoming solar radiation back into space, those same thick clouds also absorb and trap lots of solar energy.

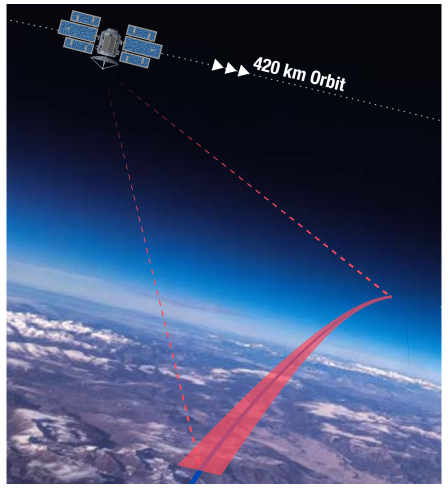
"The size of the ice crystals within high- altitude ice clouds determines the role those clouds play in regulating Earth's radiative energy system. More radiation means more heat, and more heat could lead to more powerful, energetic storm systems," said Javier Bosch, a Technologist at JPL and co-investigator for SMICES.

Deal adds that activities like deforestation and the burning of fossil fuels may increase the prevalence of cirrus clouds by spewing large amounts of fine particulates into the upper atmosphere, which then become the nuclei of high-altitude ice cloud crystals as they encounter freezing water vapor. If that's the case, then incorporating data on ice clouds could be critical for creating models that can accurately describe the relationship between those ice clouds and the prevalence of severe weather events as our climate continues to change.

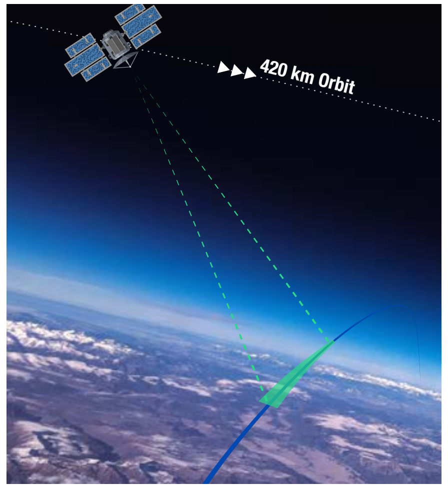
SMICES would employ several cutting-edge technologies into a single instrument to gather this critical data. In particular, its ability to selectively distribute energy to an active radar system using a pair of machine learning algorithms allows it to decrease overall power consumption by a factor of seven without compromising the strength of its radar. This means SMICES is the first compact spaceborne remote sensor fit for measuring ice crystals using radar frequencies in the 239 GHz range – which is essential for getting a clear look at cirrus clouds contributing to severe weather events.

"The artificial intelligence algorithm combs data from the three multi-band radiometers for evidence of an interesting tropospheric feature. If it finds such a feature, like a severe storm, the artificial intelligence controller activates its onboard radar and focuses it on the targeted event. The radar only activates when necessary, and that's critical for incorporating the 239 GHz active radar onto a small, cost-efficient satellite," said Deal.

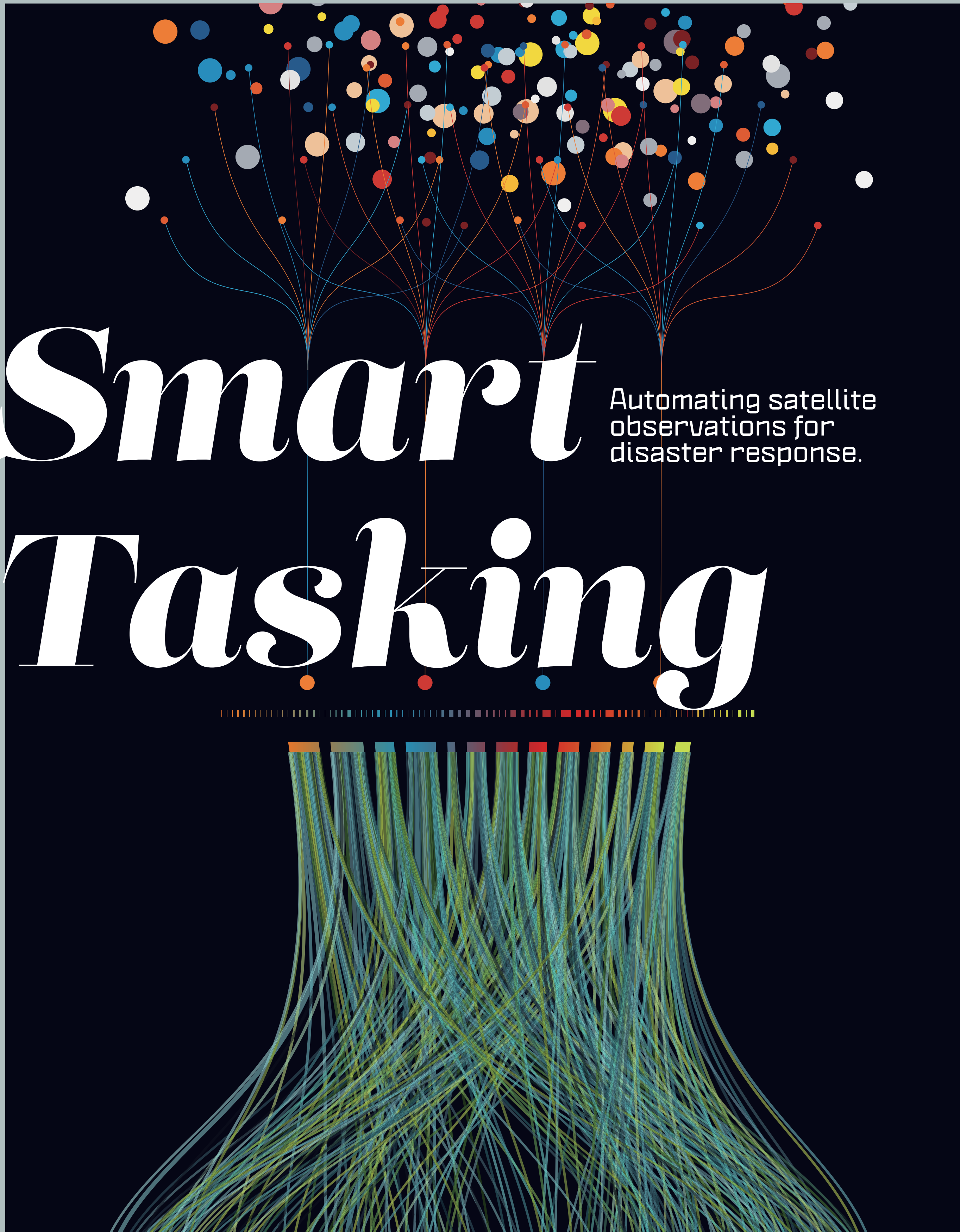
"Lingering questions about how our climate and weather will change over time can only be answered with advanced tools tailored to explore aspects of our world that are still obscure. With SMICES, we hope to shed light on one of those aspects and its impact on other Earth systems," said Deal.



▲ SMICES' passive radiometers continuously scan a 592 km cross-track swath at a 45°elevation angle.



▲ When a tropospheric feature of interest is detected, the active radar is autonomously directed at the scene.



Smart Tasking

Automating satellite observations for disaster response.

According to NOAA, disasters in 2020 cost the U.S. more than $95 billion in damages – more than any other year on record. Minimizing the impact of these disasters means dispatching much-needed aid to devastated communities as efficiently as possible.

"We can't stop disasters from happening, but we can limit the scope of these catastrophes by executing a quick, effective response," said Cathleen Jones, a researcher at NASA's Jet Propulsion Laboratory (JPL).

Jones and her team are using funding from ESTO to develop a new software system that aims to provide decision makers with essential information enabling first responders to reach victims of disasters more quickly. Their system, called "Smart Tasking," is designed to automatically alert Earth-monitoring satellites when a disaster occurs, tasking them with prioritized downlink and processing of any data that may be of use to first responders. While NASA and other space agencies already provide rescuers with data products describing disasters, they do so only after a person manually tasks satellites with assembling the necessary information.

By automating this process and instructing satellites to begin assembling data products almost as soon a disaster occurs, Smart Tasking could dramatically reduce the amount of time it takes to get invaluable information about the exact location, duration, and magnitude of disasters into the hands of first responders.

"We want to cut out the middleman. Enabling satellites to respond automatically to disasters instead of making them wait for manual instruction streamlines their ability to respond to urgent data requests," said Jones.

Satellite data is critical for coordinating disaster relief efforts. This data provides first responders more information about the extent and impact of a disaster itself, and in some cases, detailed images of the affected area. This allows rescuers to identify safe places to shelter refugees and rescuers, find passable supply and egress routes, and identify ruined infrastructure where wounded people could be trapped.

"There's no substitute for the knowledge we can provide using space-based remote sensors. These instruments have a bird's eye view of disaster zones, and that view allows first responders to get a more complete picture of a disaster situation," said Jones.

The challenge, she says, is plucking information relevant to a specific disaster from the torrents of data satellites sent back to researchers each day. Currently, it's up to human analysts to communicate with satellites about whether a disaster has occurred and decide which data might be most relevant to rescuers on the ground.

"That process could take hours or even days, and in the aftermath of a disaster, every minute counts. Even minor delays might mean the difference between life and death for those in distress," said Jones.

Smart Tasking shrinks that delay from hours or days to minutes, providing an automated interface between satellites and databases like USGS's Volcano Notification System (VNS) platform – which maintains information on volcanic eruptions – to identify and downlink data that would be useful for coordinating disaster relief. Its flexible, cloud-based architecture would accommodate multiple inputs from monitoring networks and multiple clients to service increased data requests during large disaster events, while its event databases catalogue each data request to prevent duplicate or overlapping requests from delaying data products.

"It's about speed. The faster we can image disaster areas and create these data products, the faster they can be used to improve disaster response efforts. Smart Tasking can increase the utility of NASA data for urgent response, and there's the potential to leverage this program to support studies of other dynamic Earth systems as well," said Jones.

While Smart Tasking could be used to prioritize disaster-related data gathered by numerous instruments already in orbit, Jones and her team hope that it will be especially useful for the upcoming NASA-ISRO SAR (NISAR) mission. Scheduled to launch during the summer of 2022, this joint mission between NASA and the Indian Space Research Organization (ISRO) will systematically image the Earth's surface over the course of three years to measure surface displacement as small as millimeters in size.

"Data that detailed would be incredibly useful for disaster relief purposes, but it will have to be identified and filtered from a great deal of other data first. Smart Tasking would be an excellent resource for doing this," said Jones.

▼ A volcanic eruption at Mount Sinabung, Indonesia in May 2016.

Advancing Radiation Budget Measurements

New technology offers advantages for Earth energy balance measurements.

Circling the globe multiple times each day, a network of satellites carefully measures the Earth Radiation Budget (ERB)—or, how much solar energy Earth absorbs, reflects, and emits back into space. This information helps researchers learn more about everything from daily weather patterns to climate change.

Anum Ashraf, a researcher at NASA's Langley Research Center, wants to ensure scientists continue to receive reliable information about Earth's radiant energy system for decades to come. Ashraf and her team are hard at work developing a next-generation radiometric sensor, DEMonstrating the Emerging Technology for Measuring the Earth's Radiation (DEMETER), that will not only dramatically reduce the size and weight of satellites sent to monitor ERB, but also greatly increase the utility of these instruments for meeting the evolving needs of the climate-modeling community.

From Low Earth Orbit (LEO), DEMETER will use a non-scanning, wide-field-angle optical module and a two-dimensional detector array to measure reflected solar radiation and thermal radiation emitted by the Earth between 0.2 μm and ≥50 μm. This range of radiant energy is particularly important for understanding how radiation impacts regional weather conditions and long-term climate data trends. DEMETER will improve the resolution of available ERB data by a factor of ten and—using an onboard data processing unit—provide researchers with access to ERB data in near real time, which is critical for understanding the relationship between ERB and dynamic, fast-changing Earth systems behind things like natural disasters and agricultural production.

"We need an extensive ERB data record to understand how these energy interactions affect Earth systems. DEMETER will combine state-of-the-art instrumentation with a novel, modular spacecraft design to make sure that the data record remains unbroken," said Ashraf.

Ashraf explains that researchers have monitored ERB with satellites since 1984, when the Space Shuttle Challenger delivered the Earth Radiation Budget Satellite (ERBS) into orbit. Since then, five other satellites have joined ERBS as part of the Earth Radiation Budget Experiment (ERBE) and the Clouds and the Earth's Radiant Energy System (CERES) project to track energy interactions between Earth and space.

"The data products we receive from these instruments are invaluable. By calculating the annual difference between the amount of radiation Earth absorbs and the amount of radiation Earth emits, we can clearly see how quickly the Earth is warming up due to climate change," said Ashraf.

But while these instruments have proven themselves to be particularly durable (CERES FM-1 and FM-2, launched aboard the Terra spacecraft in 1999, continue to relay useful data), most of them are approaching the end of their planned lifespans. If these instruments were to expire, it would be extremely difficult to deploy a replacement in time to preserve the integrity and continuity of the ERB data record.

"Current ERB instruments that provide global broadband coverage contain complex scanning mechanisms that increase the mass, power consumption, and the cost of the payload, requiring a budget of at least 150 million dollars to get into orbit. Sending instruments that large into LEO isn't a fast process, and even a small gap in the data record could affect our ability to create accurate models," said Ashraf.

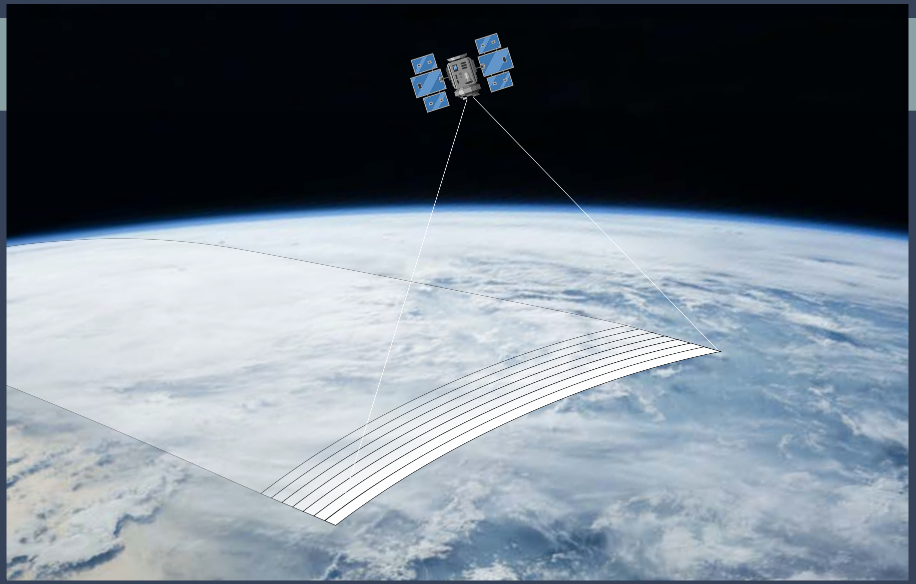
DEMETER would solve that problem. While the last ERB satellite sent into orbit weighed more than 2000 kg, DEMETER could weigh as little as 90 kg. And unlike other radiometers, DEMETER wouldn't require a complicated scanning mechanism to track radiation. Instead, DEMETER's wide-field-angle optical module would function as a simple "push-broom" sensor that could achieve superior global coverage using far less energy.

"This not only makes it less expensive to launch a satellite for tracking ERB, but also increases the number of potential flight windows such a mission could have. DEMETER would be much less difficult to get into space than other ERB monitoring systems," said Ashraf.

While DEMETER likely won't fly until 2028, a final report documenting DEMETER's system performance and a path to an accelerated flight mission is scheduled for September 2022.

"Being able to deploy ERB satellites quickly will be crucial for maximizing the value of this data record and producing invaluable insights into how ERB shapes the world we live in," said Ashraf.

▼ A DEMETER mission could achieve a scan spacing of less than 5 km per swath, increasing spatial resolution by a factor of 10 compared to current instruments in orbit. Credit: Paul Padgett/NASA



Cinematic Science

New visualization tool helps researchers explore science campaign data like never before.

Bringing together data from numerous sensor nodes and visualizing it is a critical part of the scientific process. But creating accessible visualizations isn't easy, especially when those sensor nodes communicate complex Earth-science data.

"Navigating and visualizing thousands of raw data files collected during a field campaign is an extraordinarily tedious task, and – left as is – might reduce the scientific return of the campaign," said Larry Di Girolamo, a professor of Atmospheric Sciences at the University of Illinois.

Di Girolamo collaborated with programmers and designers from the Advanced Visualization Lab (AVL) at the University of Illinois Urbana-Champaign National Center for Supercomputing Applications (NCSA) in Urbana, Illinois, to prototype a new process for communicating data from field expeditions.

The prototype uses a combination of commercially available, open source, and home-grown software to transform raw data from NASA's recent Cloud, Aerosol and Monsoon Processes Philippines Experiment (CAMP^{2}Ex) into a 3D animation and a data dashboard video. These visualizations made it easier for researchers to explore data gathered by all the instrument teams during their time in the Philippines.

In particular, these visualizations were helpful for identifying patterns between one of the largest biomass-burning events ever recorded in Indonesia and increased amounts of air pollutants in the South China Sea. Di Girolamo and the team at the AVL hope that the techniques they used to create these visualizations will help other researchers interpret and communicate data gathered during field campaigns more efficiently.

"These visualizations could revolutionize how we communicate our data to other researchers and members the public. It could make field data more accessible for anyone interested in fundamental research," said Di Girolamo.

The CAMP^{2}Ex project assembled a fleet of disparate sensors to study how aerosol particles and cloud properties could impact precipitation patterns in the Philippines and climate change around the world. The science team was especially interested in determining whether increased air pollution in South Asia might affect the amount of rain the Philippines receive annually and the amount of solar radiation Earth reflects back into space.

"Increasing levels and concentrations of certain aerosols may lead to reduced cloud cover, which limits the amount of rainfall those areas can expect. In addition, fewer reflective clouds in these areas would increase the amount of sunlight Earth absorbs, which impacts weather patterns and climate change," said Di Girolamo.

Cloud-aerosol interactions in the Philippines are extremely complicated. High-altitude clouds cover the clouds beneath them that interact with aerosols, making it difficult to observe cloud-aerosol interactions using satellites. To fill those gaps in the satellite data, CAMP^{2}Ex researchers needed to merge data from two NASA research planes, a Navy research vessel, and even the Manila Observatory in Quezon City, Philippines.

"How do you build a comprehensive picture from hundreds of thousands of files from different data sources?" said Di Girolamo. To solve this problem, Di Girolamo and the creative team prototyped two visualization products using data from CAMP^{2}EX's Research Flight 09. The first visualization was a 3D animated video that depicts the journey of NASA's P3 research aircraft as it navigates the open ocean south of Luzon. The second was a prototype of a potential future interactive dashboard, that presents much of the data gathered by airborne, seaborne, and spaceborne instruments supporting that research flight.

"In one place, you have all the information you need to locate patterns between these different data sets. As the video plays, the data in the dashboard changes in real time, so you can see exactly when and where a certain data point appeared in the record," said Stuart Levy, a senior programmer and system administrator at AVL.

The final product package, which included a two-minute video and a data dashboard depicting 76 different data variables, surpassed Di Girolamo's expectations. The visualizations helped his team link increased levels of aerosols in the Philippines to a biomass-burning event in Indonesia.

"We're excited for the possibility of organizing our other data sets like this and sharing this process with other researchers handling Earth-science data," said Di Girolamo.

▼ The CAMP^{2}Ex exhibition video, illustrating data gathered during CAMP^{2}Ex's Research Flight 09. During this flight, Di Girolamo's team gathered data linking increased levels of aerosols to the largest biomass burning ever recorded in Indonesia. Credit: NASA / AVL

Stacked Miniaturized Radiation Tolerant Intelligent Electronics

Rad-hardened computer tiles for compact space missions.

The smartphone in your pocket packs more computing power than all of NASA had at its disposal when it first sent humans to the moon. But many spacecraft still rely on outdated computers to process immense amounts of complex data.

"Software for processing data more efficiently can only be as revolutionary as the hardware hosting it. To improve data processing, that computing hardware must also keep pace," said James Yamaguchi, Vice President of 3D Electronics and Mass Storage at Irvine Sensors Corporation.

Yamaguchi is working with a team of scientists to create a novel computer technology that would allow space-based remote sensors to process data faster and more reliably. The technology, Stacked Miniaturized and Radiation Tolerant Intelligent Electronics (SMARTIE), uses advanced packaging to integrate three high-performance computer tiles into a folded-flex module with over 300 Gigaflops of computing power and 15 Theoretical Operations Per Second (TOPS) of artificial intelligence (AI) performance.

In addition to increasing the speed at which an instrument could process data, SMARTIE's stacked computer tiles would also help shield computers from interference caused by radiation in space. Perhaps most importantly, SMARTIE would bring these benefits to instruments while consuming less than 10 watts of power – less energy than the average light bulb. That means satellites equipped with SMARTIE would be much lighter and more cost-efficient than satellites that require numerous heavy batteries to power their instruments. While still in the very early stages of development, SMARTIE could eventually disrupt satellite applications across the spectrum, from Earth observation instruments to planetary exploration instruments built to study distant planets and stars.

"SMARTIE would have endless applications. It could provide autonomy to single satellites or satellite constellations using AI, enable distributed sensors where parts of the instrument are set in different spacecraft, and perform complex operations usually done on the ground to reduce data throughput," said Yamaguchi.

Powerful computers that digest data quickly use teams of processors to perform multiple calculations at the same time. With more than 150,000 processors, for example, Fugaku (currently the world's most powerful supercomputer) can perform as many as one quintillion (10^{18}) calculations each second. But processors require space and energy, two things in short supply aboard satellites tailored for maximum efficiency.

"We're talking about satellites that are tens of centimeters in size. We may be able to outfit those satellites with computers strong enough to process data in situ, but that data processing capability often takes up resources that could be used to support a stronger instrument array," said Yamaguchi

In addition, while Earth's atmosphere shields computers on its surface from most cosmic radiation, computers in space don't have that same protection. A powerful burst of radiation could impact a computer's ability to process data accurately or even destroy it completely.

"If that happens, and the satellite can no longer process or relay data, then you're flying a very expensive brick. Even computers small enough to fit practically onboard compact satellites and powerful enough to process data in situ may still be too vulnerable to radiation for use in space," said Yamaguchi

SMARTIE would solve these problems by distributing readily available computer components across a compact, flexible architecture, which would then fold into a single package only 16 mm long, 22 mm wide, and 6 mm high. These components would include an off-the-shelf multi-core processor, a graphics processing unit (GPU), and non-volatile Magnetoresistive Random Access Memory (MRAM) units, with a system controller providing adaptive redundancy to ensure gathered data isn't lost if the system suddenly loses power.

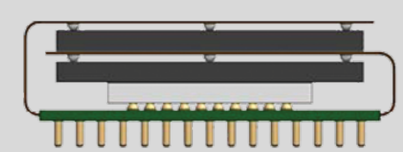
"These are standard pieces of computer hardware, but when we bring them together within this folded structure, we create a system that consumes less energy, takes up less space, helps insulate SMARTIE from radiation, and even makes it less likely that radiation will even collide with SMARTIE in the first place," said Yamaguchi.

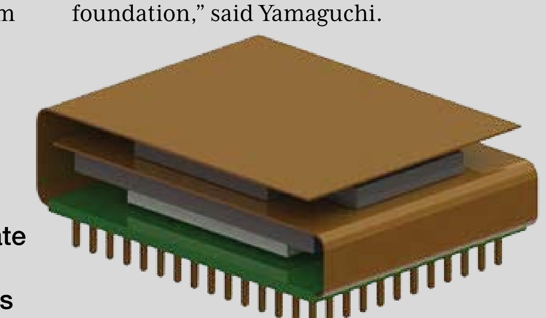
A wide variety of scientific missions dedicated to gathering data with space-based remote sensors would benefit from a computer like SMARTIE. In particular, researchers developing SMart Ice Cloud Sensing (SMICES) – an instrument that would help improve climate and weather models (see page 13) – are interested in using the technology to support their goal of measuring ice crystals in high-altitude clouds.

"The ice crystals we want to measure are best characterized using radar within the 239 GHz range, but that requires a pretty energy intensive radar apparatus. We want to run advanced AI algorithms that would only turn on the radar when necessary. For a program that complicated, we'll need to use something as powerful and compact as SMARTIE," said William Deal, PI for SMICES.

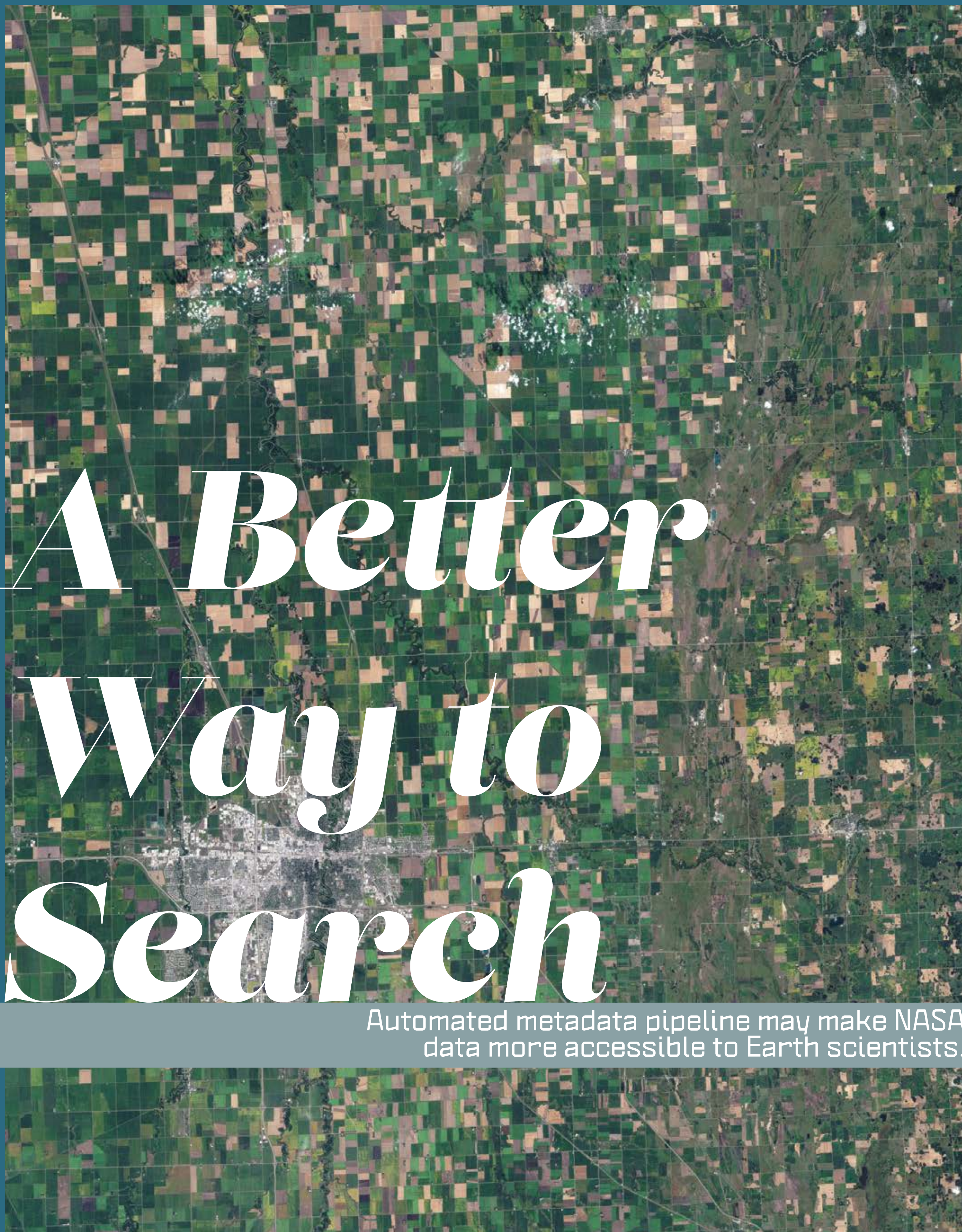
Yamaguchi is excited to see other scientists explore the possibility of incorporating SMARTIE into their instruments. Enabling researchers to accomplish their scientific objectives is, after all, what motivates his team to develop this novel component.

"We have to support one another. Every incremental step forward lays the foundation for future groundbreaking discoveries, and we hope SMARTIE will eventually become a cornerstone of that foundation," said Yamaguchi.





▲▶ **Flexible circuit in folded state before encapsulation. Credit: James Yamaguchi/Irvine Sensors**



A Better Way to Search

Automated metadata pipeline may make NASA data more accessible to Earth scientists.

If you've ever struggled to find information using an online search engine, then you know how difficult research can be. This is especially true for professional scientists, who must search through troves of data to construct their models and hypotheses.

"Finding ideal data isn't always as easy as submitting a query through a search bar. Many data sets simply aren't organized in a way that makes them visible to search algorithms," said Beth Huffer, founder and CEO of Lingua Logica, LLC. "And finding the data is only the beginning. Making it ready-to-use can be even more challenging."

Huffer wants to help researchers locate, access, and use NASA Earth science data sets with greater ease. Her project, Automated Metadata Pipeline (AMP), would automate the process of annotating NASA data sets with descriptions of what, where, when, and how the Earth science phenomena represented in the data set were measured. That information – also known as metadata – would then make it easier for search engines specializing in scientific discovery to connect researchers with data sets most relevant to their research goals and enable software developers to create Application Programming Interfaces (APIs) that connect Earth science data sets with data analysis applications. This would lead to improved models describing everything from climate change to agricultural productivity.

"NASA gathers petabytes of data each day. If we don't have an efficient process for turning that raw data into data products for scientists and decision makers, then we aren't capitalizing on the full value of that information," she added.

Robust, high-quality metadata is critical for accelerating scientific research, Huffer explains. When we search for something online, it's the context clues expressed as metadata that allow search algorithms to separate information relevant to a query from information that's irrelevant. The more descriptive metadata is, the easier it is for those algorithms to generate helpful results. High-quality metadata can even help researchers create complex models.

But manually curating metadata for NASA's Earth science data sets is an onerous and time-consuming task. There are more than 8,000 collections in the NASA Earth Observing System Data and Information System (EOSDIS) archives, and each collection can contain hundreds of individual datasets. While tools exist to assist in the metadata process, they generally rely on metadata curators manually filling in forms using drop down lists. Different curators may categorize the same information in different ways, which makes consistency hard to achieve.

"It's a common complaint among scientists that they spend more time preparing data for analysis than they spend actually analyzing data. Manual metadata curation tends to yield metadata records that use disparate terms and formats, which make it difficult to programmatically prepare and use the data with applications, even when the metadata is very descriptive," said Huffer.

AMP could help solve this problem. Huffer is working with colleagues at the Basque Centre for Climate Change (BCCC) to provide data for BCCC's ARtificial Intelligence for Ecosystems Services (ARIES) platform, a network of eco-services models. By teaching convolutional neural nets (CNNs) to organize information according to detailed ontologies, Huffer developed an AMP prototype that automatically produces metadata for the NASA data sets ARIES uses to programmatically identify data that can serve as inputs for models within the ARIES network and satisfy user requests in real time.

"For the prototype, we manually trained a convolutional neural network to recognize about 49 different variables. The neural network was then able to recognize those variables when they occurred in other data sets, and instruct the AMP data annotation module to assign the same labels to the new data sets as those that were assigned manually to the training data. So now we know that it is possible to use machine learning to generate good metadata automatically," said Huffer.

A tool that automatically generates consistent, semantically-grounded metadata for NASA Earth science data sets would be an immense boon to NASA science, improving the interoperability of NASA's petabytes of disparate data products and increasing the pace of scientific discovery. Indeed, making data FAIR (findable, accessible, interoperable, and reusable) is one of NASA's top objectives.

"Something like AMP might ultimately save both metadata curators and researchers hundreds of hours of work," said Huffer.

For an Earth scientist who works at the intersection of science and technology – such as Annie Burgess, Lab Director at Earth Science Information Partners (ESIP) – the potential benefits are considerable.

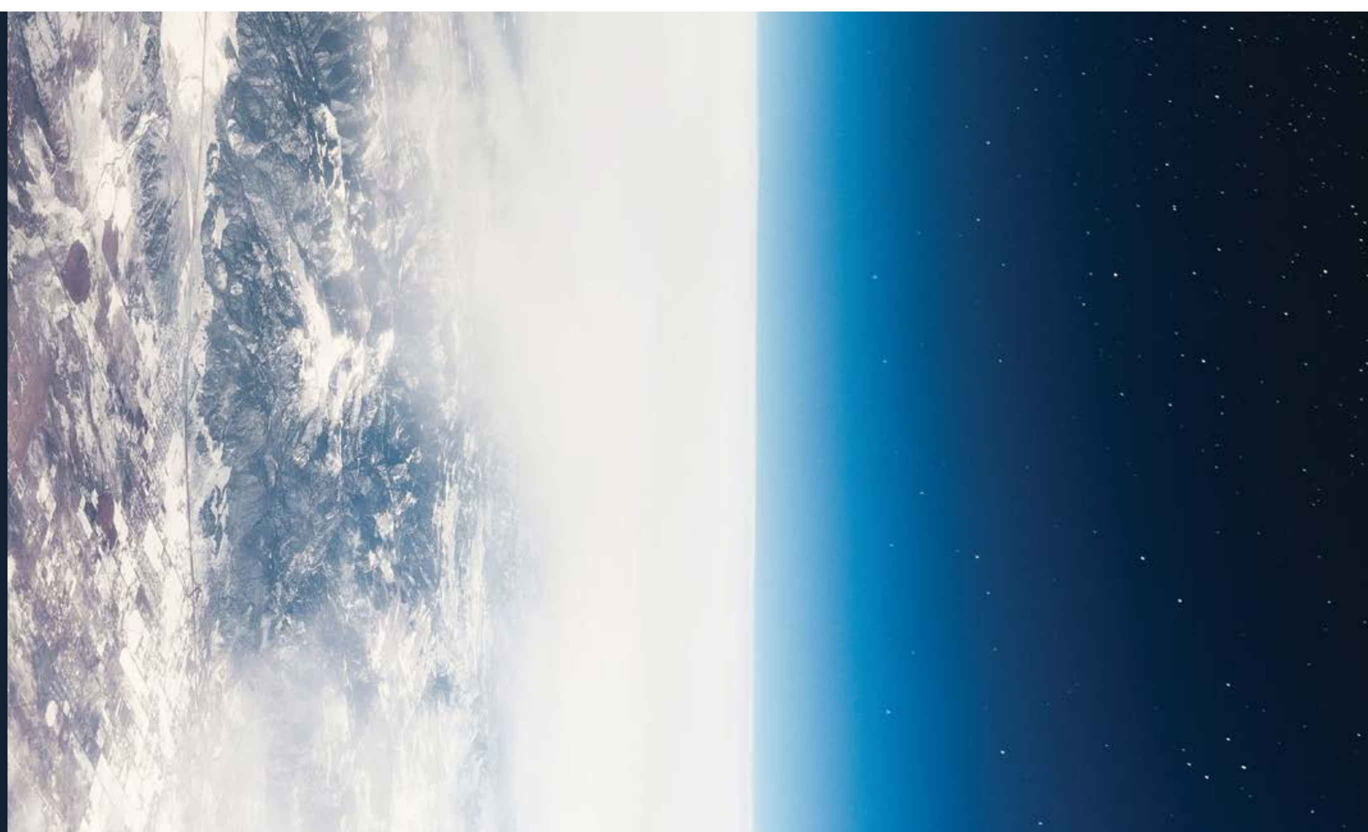
"It's very exciting. AMP has the potential to impact the entire data life cycle. By streamlining metadata generation, AMP takes a significant burden off of data professionals and researchers, ultimately streamlining the timeline from data generation to scientific insight," said Annie.

Huffer stresses that there's still a lot of work to be done, but her team's recent success with the AMP prototype is promising. She wants to continue working with NASA to develop her technology concept further and, ultimately, share AMP with metadata curators at NASA's Distributed Active Archive Centers (DAACs), who help catalogue and maintain NASA's collected Earth science data. She is also eager to explore other uses for the AMP data preparation pipeline.

"AMP will not only reduce the cost and the amount of time it takes to produce robust highly descriptive metadata records, but will also ensure that the language and format used in the descriptions are consistent," said Huffer.

Space Borne

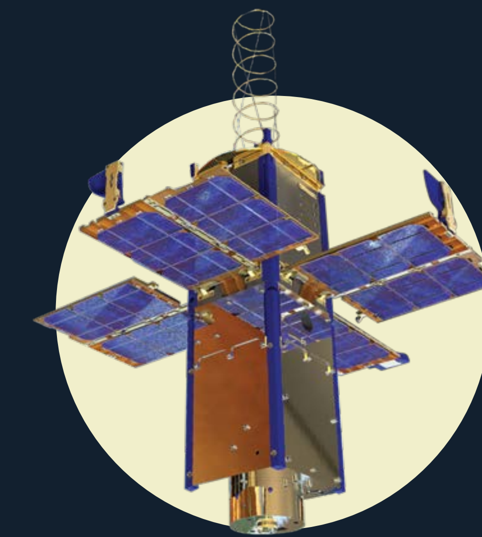
Four CubeSats prepare to take their technology demonstrations to new heights.



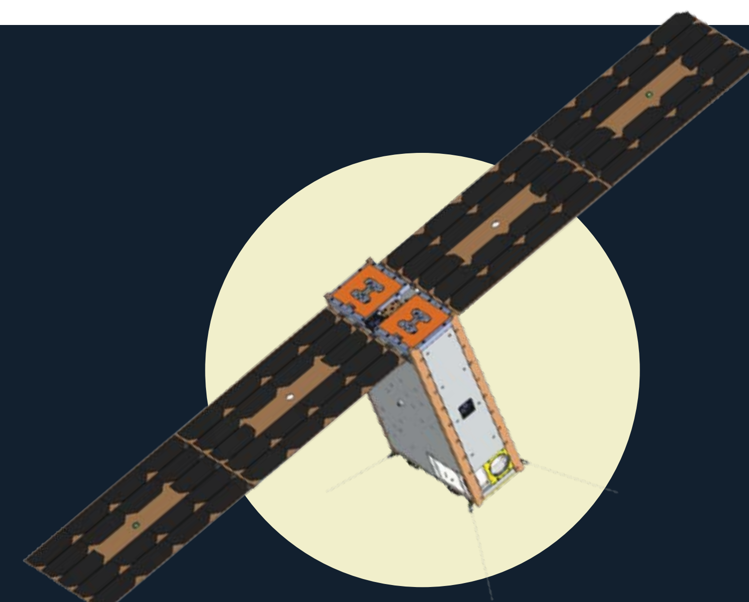
NACHOS / NACHOS 2

Atmospheric trace gases seeping from Earth's interior and pouring from human-made sources give scientists unique insights into the nuanced systems behind things like local weather patterns, the biosphere, and climate change. Spaceborne trace gas spectral imaging requires both high spectral resolution and high sensitivity, generating very large volumes of data and traditionally entailing a large satellite platform.

The Nanosat Chemistry Hyperspectral Observation System (NACHOS and NACHOS2) features an ultra-compact hyperspectral imager that pre-processes data in situ, targeting NO_2, SO_2, ozone, formaldehyde, and other gases with sufficient spectral resolution to confidently separate the trace gas signatures from the atmosphere. This would allow researchers to gather high-resolution data on atmospheric trace gases with small satellites, drastically reducing the overall cost and increasing revisit time and mission flexibility. These 3U CubeSats will help researchers determine whether constellations of CubeSat-like small satellites could gather and process high-resolution imaging data as efficiently as larger, single-platform satellites – at a fraction of the cost.



PI : **Steve Love / Los Alamos National Laboratory**
Launch Date : **NET July 2022 / NET February 2022**
Mission : **ELaNa-37 / USSF STP-S28A**
Orbit : **500 km at 51.5° / 45° inclination**



PI : **David Harber / University of Colorado / LASP**
Launch Date : **NET July 2022**
Mission : **ELaNa-39**
Orbit : **500 km 45° inclination**

CTIM-FD

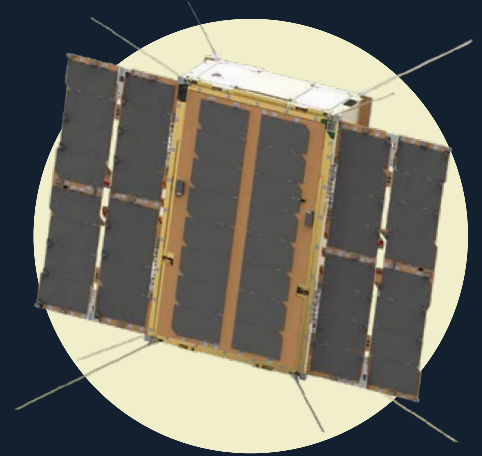
For four decades, scientists have used space-based remote sensors to measure Total Solar Irradiance (TSI), which describes the amount of solar radiation incident on the Earth from the sun from 200 to 2400 nm. TSI is a major component of Earth's radiative system, which impacts everything from local weather conditions to global climate change, and maintaining an unbroken record of TSI data is critical for understanding energy changes over time.

Currently, missions like SORCE and TSIS-1 measure TSI from space, but the 6U Compact Total Irradiance Monitor-Flight Demonstration (CTIM-FD) aims to make this measurement with equal or better accuracy in a much smaller envelope. Lighter and more compact, CTIM utilizes Vertically Aligned Carbon Nanotube (VACANT) bolometers to dramatically reduce the weight without compromising its ability to measure TSI, demonstrating an uncertainty of < 0.01% and a stability of <0.001% per year.

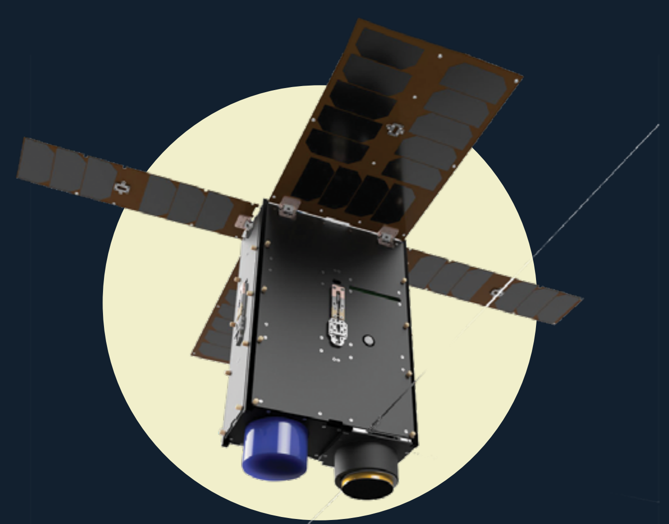
SNOOPI

Root zone soil moisture (RZSM) and snow water equivalent (SWE) play critical roles in the hydrologic cycle, impacting agricultural food production, water management, and weather phenomena. Microwave observations at P-band frequency (240-380 MHz) are needed to penetrate into the root zone of the ground, but conventional P-band radars and radiometers are prone to radio frequency spectrum access issues, and they require large antennas to obtain sufficient signal-to-noise ratio or spatial resolution.

The Signals of Opportunity P-band Investigation (SNOOPI) reuses signals from existing tele-communications satellites and therefore does not require a transmitter, making it much more cost effective and enabling measurements in all weather conditions day or night. This project will reduce the risk of utilizing this technique on future space missions, verifying important assumptions about reflected signal coherence, robustness to the RFI environment, and the ability to capture and process the transmitted signal in space.



PI : **James Garrison / Purdue University**
Delivery Date : **Before May 1, 2022**
Launch Vehicle : **SpX-25 / Falcon-9 FT**



PI : **Robert Wright / University of Hawaii at Manoa**
Delivery Date : **Before May 1, 2022**
Launch Vehicle : **SpX-25 / Falcon-9 FT**

HyTI

Magmatic gases emitted by volcanoes herald the movement of magma beneath Earth's surface and serve as an early warning of impending eruptions. Quantifying low-intensity gas emission that characterize these pre-eruptive states requires high spatial and spectral resolution long wave infrared (LWIR) measurements to allow both the detection and quantification of gas fluxes and how they vary in time. Hyperspectral imaging with high spatial resolution in the LWIR has not yet been achieved from space.

In response to this need, the Hyperspectral Thermal Imager (HyTI) aims to demonstrate high-spatial, spectral, and temporal resolution thermal infrared (TIR) imagery acquisition from low Earth orbit. From a 430 km orbit, the HyTI instrument will have ground sampling resolution of 60 m for 25 spectral samples in the 8.0-10.7 micron wavelength range, with narrow-band NEdT (noise equivalent variation in temperature) of less than 150 mK. A future constellation of 25-30 HyTI satellites could monitor Earth's volcanoes for signs of impending eruptions and map soil moisture for crop management at lower cost than a single, conventional satellite.

Looking ahead, four more ESTO teams set their sights on validating technologies in space.

ACMES

The Active Cooling for Methane Earth Sensors mission will test a complete, end-to-end solution for active thermal control of cryogenic instruments on SmallSats. Current cryocoolers can be too large for CubeSats, limiting the types of instruments that can be used on small satellite buses. ACMES will demonstrate an engineering solution that will provide a 70% reduction in radiator size for a given heat rejection capability. Simultaneously, this mission will validate a narrow-band infrared spectrometer designed for space-based detection of methane sources. PI: Charles Swenson / Utah State University

ARCSTONE

The data provided by on-orbit, Earth-observing instruments is only as good as its calibration accuracy. ARCSTONE will validate a calibration technique that uses the Moon as a high-accuracy calibration reference. With its invariant surface, the Moon is an extremely stable natural solar diffuser, making it an excellent exo-atmospheric calibration source. ARCSTONE will provide the in-space lunar spectral reflectance measurements needed to establish an absolute lunar standard that could be used by most Earth-observing sensors for increased accuracy.
PI: Constantine Lukashin / NASA LaRC

ARGOS

The Aerosol Radiometer for Global Observation of the Stratosphere will measure stratospheric aerosols by collecting limb scattering data at several wavelengths in multiple viewing directions simultaneously. This technique would provide more balanced measurement sensitivity over instruments currently in orbit like the Ozone Mapping and Profiling Suite (OMPS), greatly constraining uncertainty in global aerosol modeling. The enhanced spatial and temporal sampling enabled by ARGOS could also improve our ability to project the short-term economic impacts of the hazards that follow volcanic and pyrocumulonimbus perturbations.
PI: Matt DeLand / SSAI

SUMRS

The Super Uncooled Multiband Radiometer Sensor is a thermal imaging radiometer boasting a 2x increase in resolution over previous instruments. Funded through the Sustainable Land Imaging Technology (SLI-T) program that is developing the next generation of Landsat technologies, this instrument will be able to provide accurate temperatures of a wide range of materials through the extraction of object emissivity using multi-band radiometry.
PI: Phil Ely / Leonardo DRS

Expanding capabilities for studying storms across the globe.

Storm Chaser

Blistering hurricanes cost coastal communities around the world millions of dollars and thousands of lives each year. Learning more about these intricate storm systems would allow researchers to improve predictive weather models and forecast severe storms with greater ease.

"We can't control severe weather events, but we may be able to minimize their impact on human populations by giving people more time to prepare," said Christopher Ruf, professor of Climate and Space Science at the University of Michigan, Ann Arbor.

Ruf, who also serves as the principal investigator for NASA's Cyclone Global Navigation Satellite System (CYGNSS) mission, has already developed a small constellation of micro-satellites that helps scientists measure wind speeds over Earth's oceans. Now, Ruf wants to develop a new bistatic radar receiver that will substantially increase the quality of data gathered by future CYGNSS satellites.

"These satellites have been a great asset to scientists looking to study not just cyclones, but also things like near-surface soil moisture and the extent of microplastic debris in the ocean. This new receiver will make future components of the CYGNSS system even more valuable to Earth scientists," said Ruf.

A Pegasus XL rocket brought the first payload of CYGNSS instruments into Low Earth Orbit (LEO) in 2016. Spaced about 12 minutes apart, these eight small satellites use signals from existing GPS instruments to observe Earth via scatterometry. While most scatterometric instruments feature both a transmitter and a receiver, CYGNSS satellites take advantage of existing radar signals to reduce the overall complexity and cost of operating in space.

"Scatterometry uses a transmitter to beam radar signals to Earth's surface and a receiver to determine how strongly those emitted signals reflect off of Earth back into space. Within a single instrument package, that payload becomes pretty heavy. By tapping into transmitted radar signals produced by GPS satellites already in orbit, we can remove the transmitter component from our instruments and still produce excellent data," said Ruf.

But there's room for improvement. CYGNSS satellites currently orbiting Earth can only process four transmission signals at a time, which limits their accuracy. In addition, CYGNSS satellites can only process L1 signals, which are transmitted at a frequency of 1575.42 MHz. This has a negative impact on both horizontal and vertical resolution of gathered data, making it difficult to use CYGNSS to study things like altimetry and polar ice extent.

"CYGNSS has performed remarkably well these past few years, but as we expand its mission to include more science areas, we'll need to improve certain components of these instruments," said Ruf.

His next-generation Global Navigation Satellite System (GNSS) bistatic radar receiver would do just that, increasing the scientific utility of CYGNSS instruments for studying complex Earth systems. Instead of only processing four L1 radar signals from GPS satellites, future instruments equipped with this receiver would be able to process as many as fourteen L1 and L5 radar signals from both GPS and Galileo satellites.

"As a direct result of these changes, horizontal resolution will be improved by a factor of three, vertical resolution will be improved by a factor of ten, and spatial coverage by a factor of at least two, perhaps even four," said Ruf.

That improved resolution will enable researchers to study storms better, observe polar ice extent more clearly, develop better models for flood prediction, and even measure sea surface at a level of detail that surpasses current CYGNSS instruments by a factor of ten.

"To have these capabilities onboard cost-efficient small satellites is pretty incredible. We'll be able to produce excellent science at a much lower cost," said Ruf.

While the bistatic radar receiver isn't quite ready to venture into space, it is ready for substantial airborne testing. Partnering with the New Zealand Ministry of Business, Innovation and Employment, the New Zealand Space Agency, Air New Zealand, and the University of Auckland, Ruf plans to fix a prototype of his sensor to a Bombardier Q300 passenger plane. Ruf's sensor will gather oceanic data as the plane services routes across New Zealand, helping his team determine if the instrument is ready for spaceborne applications.

"We're thrilled to be working with our colleagues in New Zealand to prepare this radar receiver for space. To take something that was just an idea and develop it into a working prototype has been very satisfying, and we're excited to send this instrument into space someday soon," said Ruf.

▼ The NGRx integrated receiver. Credit: Chris Ruf / UMich

New Observing Strategies

Novel software testbed socializes sensors for future cooperative networks.

Innumerable sensors around and beyond our world supply scientists with the data they need to study intricate Earth phenomena. But each individual sensor can only observe so much, making it difficult for researchers to fully understand these massive, complicated Earth systems.

"Working together, communities of remote sensors help us create a full picture of Earth events. But uniting sensors from different entities together into one system isn't always easy," said Paul Grogan, researcher with the Systems Engineering Research Center and Director of the Collective Design Lab at the Stevens Institute of Technology.

With support from ESTO, a collaborative team of researchers from numerous organizations – including JPL, GSFC, ARC, LaRC, USGS, University of Maryland, University of Southern California, and MIT – recently demonstrated a novel software platform that will help networks of dispersed sensors share information with each other more efficiently. The platform, New Observing Strategies Testbed (NOS-T), merged data from ground-based, spaceborne, and airborne sensors scattered across the country into a single data product that describes the 2019 Midwest floods, which caused more than $1 billion worth of damage.

"We had a very successful demonstration. NOS-T helped us see how a diverse variety of events contributed to these severe floods in the Midwest – including increased levels of river ice, unusually deep layers of soil frost, and heavy precipitation. It's hard to see that complete picture using just a single set of sensor nodes," said Jerry Sellers, a researcher at the Stevens Institute of Technology who worked with Grogan to design the NOS-T platform.

16 researchers and data professionals from a dozen different institutions worked together during the NOS-T demonstration, generating an event-driven software architecture to leverage USGS river gauges, NASA weather satellites, university soil-moisture sensors, and other instruments together into a collaborative sensing architecture, which provided researchers with a far more comprehensive view of the 2019 floods than any single sensor ever could.

"We have all these sensors installed for individual purposes, but the data they gather could actually be combined to accomplish more scientific objectives. We just have to implement a communications fabric that enables these sensors to share their data with one another more easily," said Grogan.

NOS-T is a critical next step in NASA's New Observing Strategies (NOS) initiative, an ESTO-led push to develop new information technologies that will allow researchers to operate dynamic, multi-element sets of observing assets.

"Working together, existing sets of Earth-monitoring sensors could be used to gather new or improved observations of Earth's complex systems. Building information systems that enable these connections could help scientists accomplish their research objectives without starting from scratch and developing completely new instruments," said Jacqueline Le-Moigne, ESTO's AIST program manager.

Ben Smith, an ESTO Associate at JPL who coordinated the NOS-T flood-case demonstration, explains that NOS technologies will become critical for quickly developing in-depth data products describing things like severe weather events and climate change.

"The ability to coordinate intelligently among in situ sensors, forecast models, and satellites could produce a more comprehensive picture of events like floods as they are happening," he said.

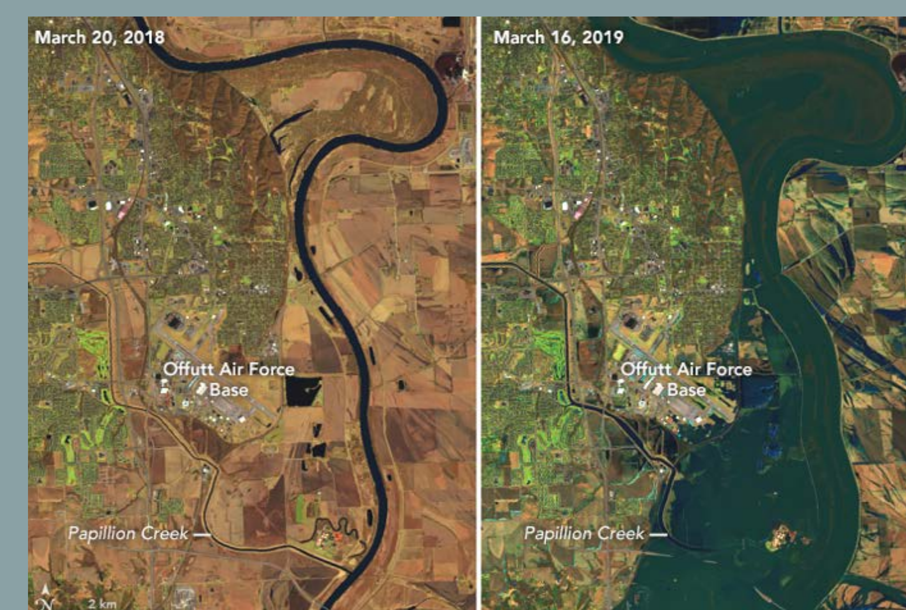
Bringing together disparate sensor networks operating in different domains and managed by different organizations, even different countries, is no easy task. They may not have the same hardware, use the same interface protocols, or even speak the same programming language.

"It's kind of like being in an online meeting where everyone is trying to talk at once. At the end of the day, very little information has been shared. And if folks in the meeting are all speaking different languages, it's even harder to communicate," said Grogan.

But a testbed platform like NOS-T gives researchers an opportunity to socialize different sensors using real-world data. NOS-T can simulate Earth science scenarios, allowing researchers to prototype different techniques for connecting different sensors before bringing those techniques to the field. A cloud-based software, NOS-T is accessible simultaneously to researchers as geographically dispersed as their sensor nodes.

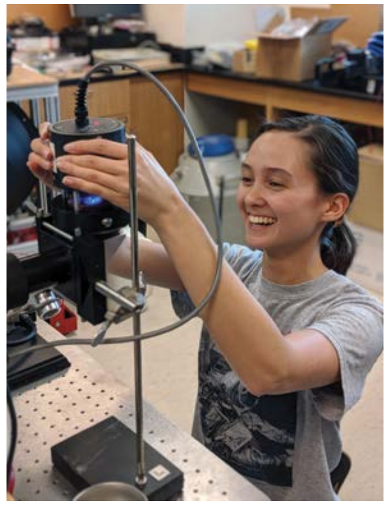
"We've shown that the NOS-T technology concept is feasible. Now we just need to continue developing these concepts to incorporate more diverse groups of sensor networks, including industry, government partners and academia," said Grogan.

▼ Landsat images showing extent of flooding in Nebraska in 2019. Credit: NASA / Landsat 8



Student Spotlight

Students are vital to many technology development efforts. In FY21 alone, at least 104 students from 44 institutions were involved in active ESTO projects. Here are a few highlights from the past year.



Chiara Ferrari-Wong

is pursuing a Ph.D. in Earth and Planetary Science at the University of Hawaii at Manoa. Her work involves performance modeling and instrument calibration for the Hyperspectral Thermal Imager (HyTI) CubeSat, an InVEST project led by principal investigator Rob Wright (see page 28). HyTI is scheduled to launch to, and be subsequently deployed from, the International Space Station in May 2022. Once in orbit, HyTI will demonstrate high spectral and spatial resolution thermal infrared imaging from a 6U CubeSat for the first time, which could be particularly useful for volcanic and hydrology remote sensing. “What’s really compelling for me is the instrument design aspect,” said Chiara, “the hands-on work instead of just the theory.” In her spare time, Chiara enjoys practicing ballet and teaching dance at a local studio.

Jiuyi Zhang

Working alongside IIP principal investigator Yongxiang Hu of NASA’s Langley Research Center, Jiuyi Zhang combined cutting-edge techniques in quantum nanophotonics and single photon counting to demonstrate a new method for measuring the absorption spectra in the atmosphere. The experiment, which utilized a frequency swept, high-finesse cavity resonator on chip- and dual-channel photon-counting systems, showed excellent agreement with established data sets and represents a step toward smaller, lighter remote sensing instruments. The work was published in April 2021 as a feature article in Applied Physics Letters. Jiuyi is pursuing a Ph.D. in Physics at the Stevens Institute of Technology in New Jersey.

James Smith,

shown here in the Microwave Earth Remote Sensing Lab at Brigham Young University, is a Masters student in Electrical Engineering working with IIP principal investigator David Long on the Global L-band Ocean and Water Observing System (GLOWS) project. Specifically, James is modeling the lens antenna and conducting system performance prediction for GLOWS, an active/passive microwave sensor to measure soil moisture, sea surface temperature, freeze/thaw, and sea ice thickness. James was also a participant in BYU’s first CubeSat mission – Passive Inspection CubeSats (PICS) – launched in January 2021, and is coaching a team of students working on a second mission.

Kira Hart Shanks & Jeremy Parkinson

have spent the last few years getting an infrared polarimeter ready for a ride on a NASA high-altitude balloon. Both are graduate students in the University of Arizona Wyant College of Optical Sciences; Kira is pursuing a Ph.D. and Jeremy is pursuing a MS. Their instrument, the InfraRed Channeled Spectro-Polarimeter (IRCSP) was designed as a part of the ESTO/IIP-funded SWIRP (Submm-Wave and Longwave Infrared Polarimeter) project for cirrus ice cloud measurements. Kira is also the recipient of a 2020 NASA FINESST award in Earth science in which she proposed the balloon flight and subsequent data analysis. The IRCSP uses uncooled microbolometers, and the project team sought to test the technology more thoroughly before utilizing on SWIRP. In late August, the IRCSP flew successfully out of NASA's Columbia Scientific Balloon Facility in Fort Sumner, NM. A first pass at the data showed successful operation at altitude (just over 100,000 feet) with evidence of polarized signal.

Benjamin Adarkwa & Maya Mital

Over Summer 2021, two aerospace engineering undergraduate interns joined the ESTO AIST program to work on the NASA Digital Twin Project. Maya Mital, at the University of Colorado, Boulder, and Benjamin Adarkwa, at the University of Maryland, College Park, explored AI for the analysis of satellite and in situ air-quality data. Their work was used to create a virtual representation – a "digital twin" – of local air quality in the College Park, MD, area, including factors such as day/time, temperature, humidity, and bus emissions. In this way, a digital twin could be used to detect and predict potentially dangerous anomalies.

Benjamin is a self-taught multi-instrumentalist, focusing on guitar, and Maya enjoys pursuing the arts as well as volleyball and robotics.

The 2021 Earth Science Technology Forum (ESTF2021) was held virtually again this year due to the COVID-19 pandemic. ESTF2021 consisted of eight virtual sessions, held on Thursdays from May through early July. Each 2.5-hour session included a targeted set of technology presentations around an Earth science theme, followed by a panel discussion.

ESTF2021 showcased a broad array of technology research and development projects related to NASA's Earth science endeavors. Over 650 attendees registered for the event. The full conference proceedings, including presentation files and video recordings of the talks, are available at esto.nasa.gov/forum/estf2021.

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