National Aeronautics and
Space Administration

2024 Annual Report

Earth Science Technology Office

Executive Summary

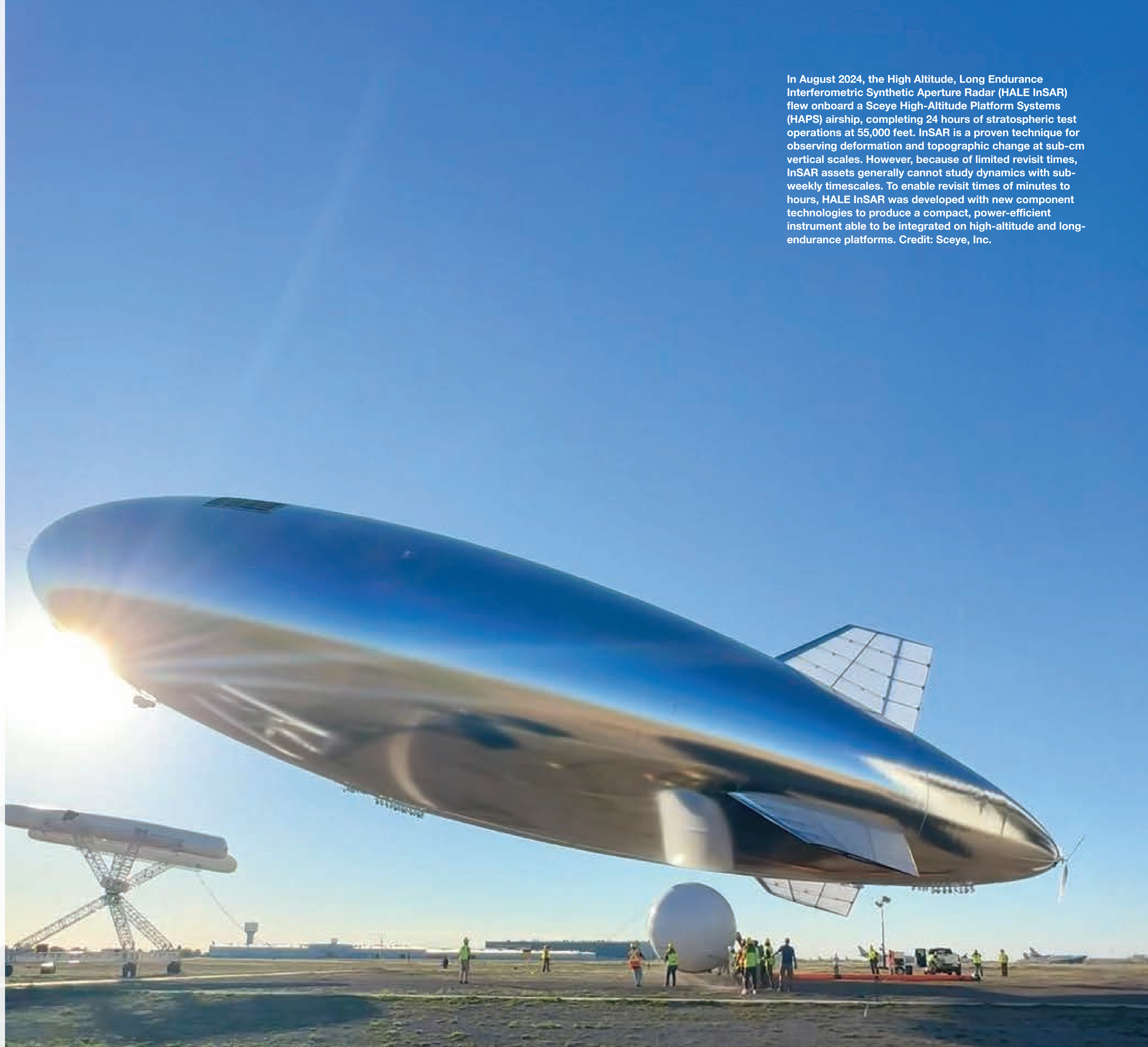
For decades, NASA has used the unique vantage point of space to measure Earth's varied, connected systems, to understand changes resulting from human and natural effects. Technology developments from NASA's Earth Science Technology Office (ESTO) have enabled breakthroughs in the measurement of our planet, as well as new tools and capabilities for disaster response and policy-making. We're very proud of the accomplishments of ESTO-funded projects during 2024, with numerous technology advances for Earth science as well as the competitive selection of new projects. Nearly half of active ESTO technology projects advanced at least one Technology Readiness Level (TRL), and at least 20 projects were transitioned to follow-on development efforts or infused into Earth observing missions, operations, or commercial applications. More than 250 students – high school through PhD – were directly involved in ESTO-funded projects this year. I am especially proud of our entrepreneurship prize challenge, which engaged minority-serving institutions to develop technologies to address the problem of wildland fire management. In addition to receiving a cash award, the three winning teams presented their ideas to venture capitalists, and engaged in a startup accelerator program that helped turn their ideas into business ventures.

New projects were added through competitive solicitations under the In-space Validation of Earth Science Technologies (InVEST) and the Wildfire Science, Management, and Disaster Mitigation (FireSense Technology) program. We expect to announce new awards under several other programs in FY25, including the Instrument Incubator Pro gram (IIP), the Advanced Information Systems Technology (AIST) program, and the Decadal Survey Incubation (DSI) program.

We are also pleased to announce that Elizabeth (Betsy) Forsbacka was selected as the new Deputy Associate Director in September. Alongside our principal investigators, program managers, staff, and the larger Earth science community, Betsy and I are committed to continuing ESTO's legacy as a respected and successful organization, enabling the next generation of groundbreaking technologies.

Michael Seablom
Associate Director for Technology
NASA Earth Science Division

Betsy Forsbacka
Deputy Associate Director for Technology
NASA Earth Science Division



In August 2024, the High Altitude, Long Endurance Interferometric Synthetic Aperture Radar (HALE InSAR) flew onboard a Sceye High-Altitude Platform Systems (HAPS) airship, completing 24 hours of stratospheric test operations at 55,000 feet. InSAR is a proven technique for observing deformation and topographic change at sub-cm vertical scales. However, because of limited revisit times, InSAR assets generally cannot study dynamics with sub-weekly timescales. To enable revisit times of minutes to hours, HALE InSAR was developed with new component technologies to produce a compact, power-efficient instrument able to be integrated on high-altitude and long-endurance platforms. Credit: Sceye, Inc.

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 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

ESTO
EARTH SCIENCE TECHNOLOGY OFFICE

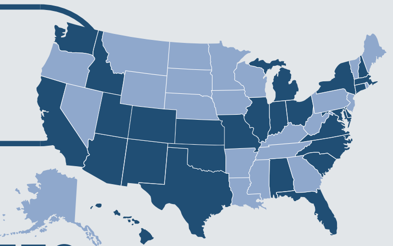
BY THE NUMBERS

14 PROJECTS ADDED

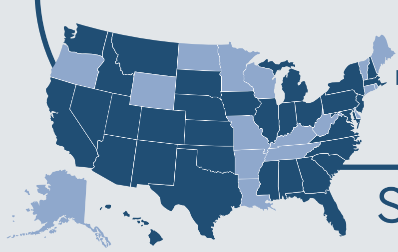
157 PROJECTS ACTIVE IN FY24

PROJECTS GRADUATED 31

70 UNIQUE PI ORGS



27 STATES



142 UNIQUE CO-I ORGS

STATES 33

253 STUDENTS

69 INSTITUTIONS

107 JOURNAL ARTICLES

362 CONFERENCE PUBLICATIONS

4 TECH DEMOS ON ORBIT

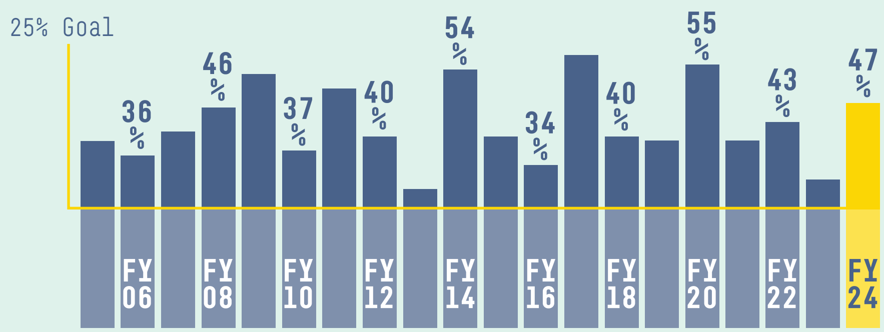
7 PROJECTS AIRBORNE TESTED

1 PATENT

FY24 METRICS

With over 1,110 technology investments made since 1999 and an active portfolio of 157 projects during FY24 (October 1, 2023, through September 30, 2024), ESTO drives innovation, enables future Earth science observations, and strengthens NASA's capability for developing and advancing leading-edge technologies. To highlight the FY24 achievements, what follows are the year's results tied to ESTO's performance metrics.

[GOAL 1: Tech Readiness]



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

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

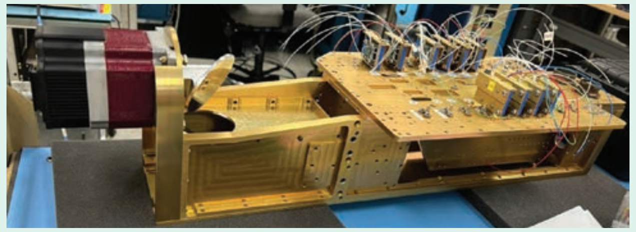
47% of ESTO technology projects funded during FY24 advanced at least one TRL over the course of the fiscal year, and at least 16 projects advanced more than one TRL. Although the percentage of TRL advancements tends to be higher in years with large numbers of completing projects, ESTO has consistently exceeded this metric in every fiscal year since inception. The average annual TRL advancement for all years going back to 1999 is 43%.

[GOAL 2: Infusion]

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

In this fiscal year, at least nine ESTO projects reported infusion into science measurements, airborne campaigns, data systems, or other operational activities. Additionally, at least 11 projects reported a transition to follow-on development opportunities. Three notable examples follow.

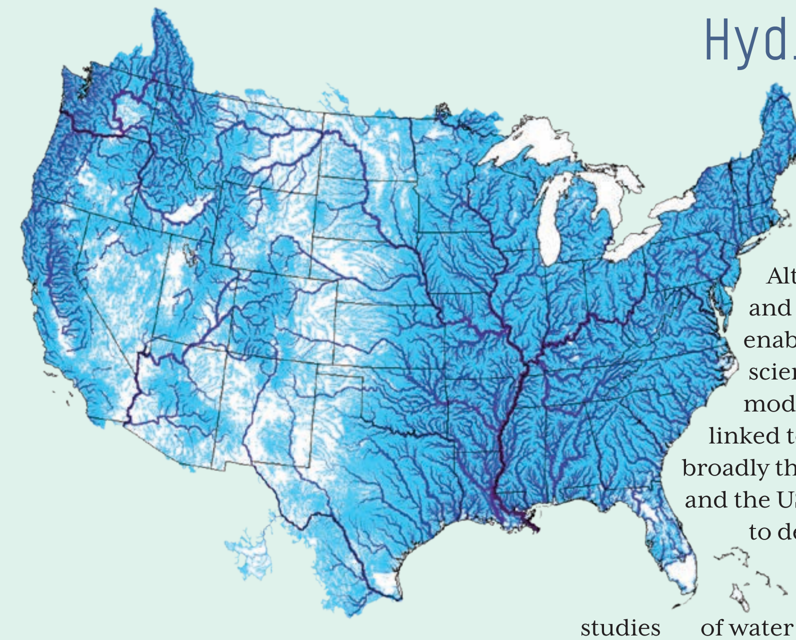
Infusion Highlight: Reducing Aviation Contrails



Final assembly of the YTHP in the lab. Credit: W. Deal / Northrop Grumman

In late 2023, a component technology was selected by the Department of Energy (DoE) for a "Contrail Avoidance System" project. The Y-Band Temperature and Humidity Profiler (YTHP), developed by Northrop Grumman and the Jet Propulsion Lab, is a forward-scanning passive sounder in GHz frequencies that measures mixing ratios of oxygen and water vapor. Optically-thin contrail cirrus clouds, which allow visible light to pass through but can trap infrared light, have been identified as a contributor to global warming. While research is ongoing to define the impact, estimates suggest air traffic can increase cirrus cloud cover by as much as 20% within busy corridors, and DoE is focused on in-flight reduction techniques. Studies show that changing altitude by as little as 1,000 feet can eliminate most contrail cirrus. As a contrail prediction and avoidance system, the YTHP would measure the environmental conditions above, below, and in front of an aircraft and the system would employ a predictive algorithm to instruct the flight crew to proactively respond to regions conducive to long-lived cirrus formation before they enter the area.

Infusion Highlight: Hydrologic Modeling Tools Widely Adopted



SUMMA/MizuRoute simulations of mean annual streamflow for the National Hydrography Dataset (NHD++) network. Credit: A. Wood / NCAR

An information systems project at the National Center for Atmospheric Research (NCAR) has refined and implemented several hydrologic modeling tools – including the Structure for Unifying Multiple Modeling Alternatives (SUMMA) hydrologic modeling framework and the MizuRoute channel routing post-processor – to enable researchers and practitioners to access emerging science advances in climate downscaling and hydrologic modeling for water resources planning. The tools were linked to the NASA Land Information System (LIS) and more broadly they are now being used by the Army Corps of Engineers and the US Bureau of Reclamation as a key modeling resource to develop US-wide datasets and guidance for future hydroclimate conditions. These analyses will in turn be used as input for the planning, policy and management studies of water resources systems as well as for Secure Water Act reports to Congress. Additionally, SUMMA is being connected to the NOAA National Water Modeling platform (NextGen) as an option for forecasting operations, and the Department of Energy has plans to further develop SUMMA to support their own Secure Water Act reporting in the future. Most recently, SUMMA and MizuRoute have been embedded in the National Weather Service Community Hydrologic Prediction System (CHPS) as an experimental option for US River Forecast Centers (RFCs).

Infusion Highlight: Earth System Explorers Heritage

In early May, NASA announced four science investigations selected for Step 2 Concept Studies under Earth System Explorers, a program to conduct scientific investigations of focused scope that can be developed relatively quickly. All four proposed investigations include ESTO technology heritage:

STRIVE **Stratosphere Troposphere Response using Infrared Vertically-Resolved Light Explorer**

Two ESTO projects – the Multi-Angle Stratospheric Aerosol Radiometer (MASTAR) [2016, NASA GSFC] and the Global Observation of the Stratosphere (ARGOS) hosted payload instrument [2020, NASA GSFC] – played key roles in advancing the stratospheric aerosol profiling technique to be used on STRIVE.

ODYSEA **Ocean DYnamics and Surface Exchange with the Atmosphere**

ODYSEA builds directly on the legacy of the airborne Ka-band Doppler Scatterometer for Measurements of Ocean Vector Winds and Surface Currents (DopplerScatt) which demonstrated simultaneous measurements of ocean surface vector winds and currents for the first time in 2016. [2013 and 2016, JPL]

EDGE **Earth Dynamics Geodetic Explorer**

The lasers on EDGE rely on technology developed for the NASA airborne Land, Vegetation, and Ice Sensor (LVIS) instrument [NASA GSFC]. ESTO investments helped refine the LVIS instrument between 2009 and 2015.

CARBON-I **The Carbon Investigation** can trace its heritage to the Snow and Water Imaging Spectrometer (SWIS) [2013, JPL] that advanced the Dyson spectrometer design that led to the Earth Surface Mineral Dust Source Investigation (EMIT) Earth Venture Mission, in turn a precursor to Carbon-I.

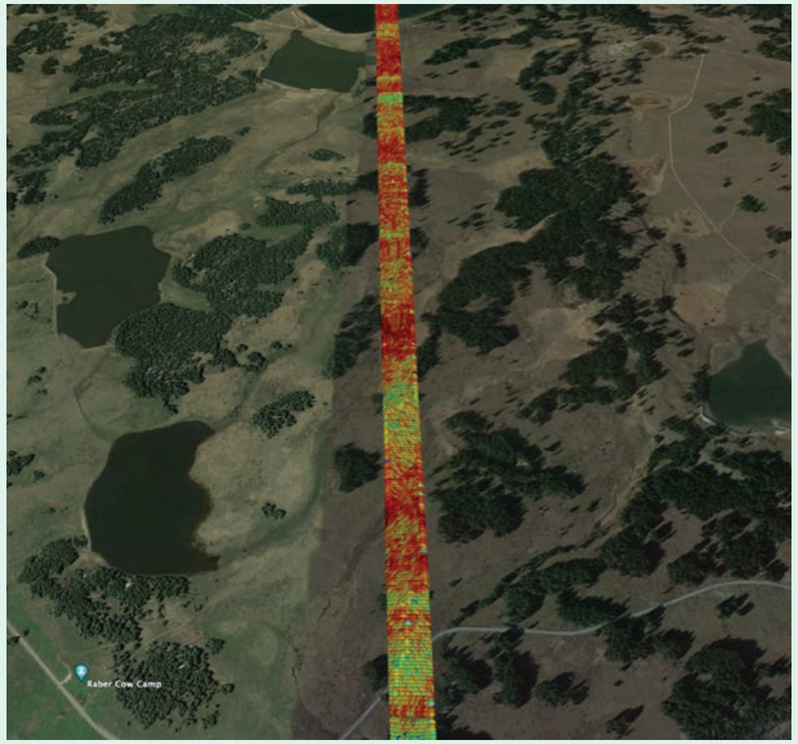
FY24 METRICS

[GOAL 3: Science Measurement]

>> Enable a new science measurement or significantly improve the performance of an existing technique. Several projects satisfied this goal in FY24. One notable example follows:

Project Highlight: A New, Compact Instrument for Snow and Soil Moisture

The SoOpSAR crew in front of the Super King Air. Credit: JPL



Extreme drought is increasingly afflicting the American West and other regions worldwide, impacting everything from food prices to water management to conservation efforts. One key to understanding water availability challenges is an advanced, efficient sensor for measurements of snow accumulation, snow melt, and soil moisture.

The Signals of Opportunity Synthetic Aperture Radar (SoOpSAR), a recently-completed project at the Jet Propulsion Laboratory, is a unique remote sensing instrument that utilizes the radio signals produced by telecommunications satellites to gather information about mountainous snowpacks.

By taking advantage of existing high-power radio transmissions already bouncing off Earth's surface, SoOpSAR can collect detailed data describing fallen snow with no active transmitter of its own. This allows SoOpSAR to reduce weight and power consumption without sacrificing data resolution.

A typical spaceborne radar instrument might consume more than 1,000 W of power, requiring large solar panels as well as a large deployable antenna. In contrast, SoOpSAR only consumes about 20-30 watts and is small enough to fit onboard a small satellite platform.

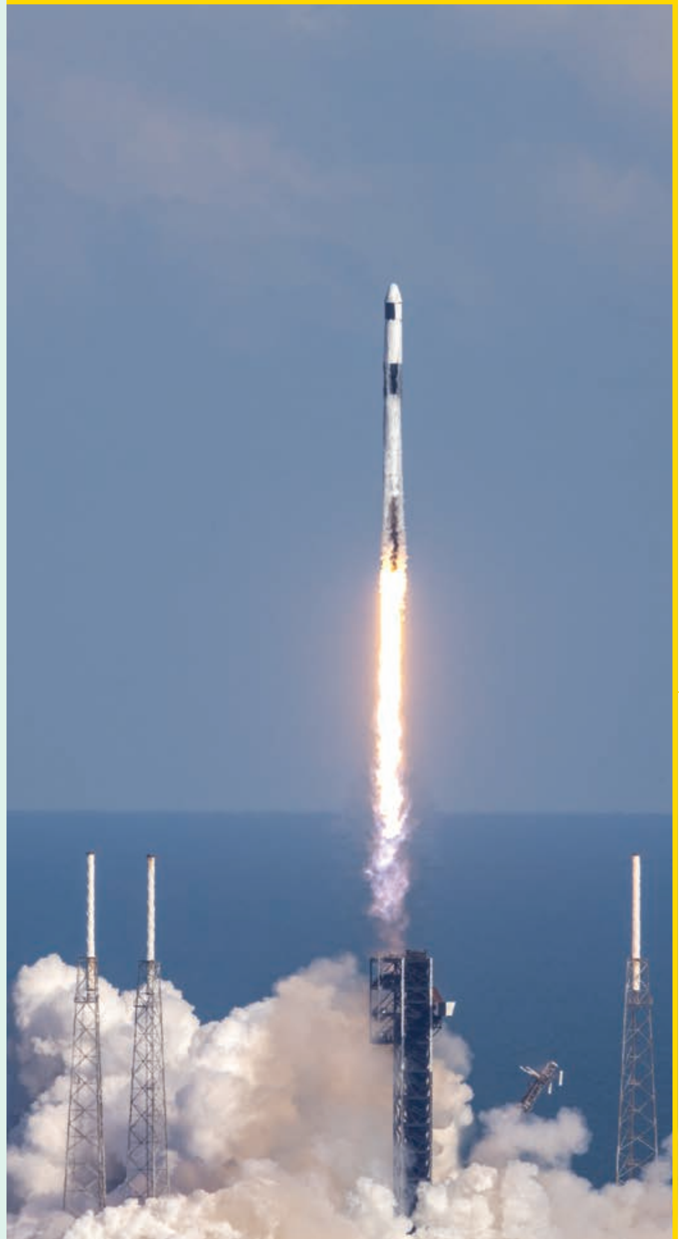
In early 2023, SoOpSAR completed 15 science test flights onboard the NASA AFRC Super King Air, over Grand Mesa, Colorado and Sagehen Creek, California. The data collected was used to mature the instrument and help refine a future mission concept involving a constellation of SmallSats. Such a constellation could potentially achieve high-resolution SAR imaging with better than 100-meter spatial resolution over a 500 km swath and allowing for complete coverage of mid- and high-latitudes every three to four days.

A preliminary SoOpSAR image overlaid on a Google map. The intensity of reflection (pseudo color) has a spatial resolution of 10m, and the image was produced using more than 40 flight passes. Credit: S. Yueh / JPL

FY24 PROGRAM UPDATES

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.



11 Projects Active in FY24

2 Projects Added in FY24

- **ODIN: Optomechanical-Distributed instrument for Inertial sensing and Navigation** – Felipe Guzman, University of Arizona
- **Gravitational Reference Advanced Technology Test In Space (GRATTIS)** – John Conklin, University of Florida

1 Projects Graduated

- **NanoSat Atmospheric Chemistry Hyperspectral Observation System (NACHOS)** – Steven Love, Los Alamos National Lab

InVEST Project Highlight:

ESTO sent two InVEST projects to space this year, both launched March 21 aboard SpaceX's Dragon cargo spacecraft as part of the company's 30th commercial resupply mission to the International Space Station. Learn more about the Signals of Opportunity P-Band Investigation (SNoOPI) and the Hyperspectral Thermal Imager (HyTI) 6-unit CubeSats on page 32.

Credit: C. Bailey / Florida Today

FY24 PROGRAM UPDATES

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 and 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.

FireSense Technology

13 Projects Active in FY24

5 Projects Added in FY24

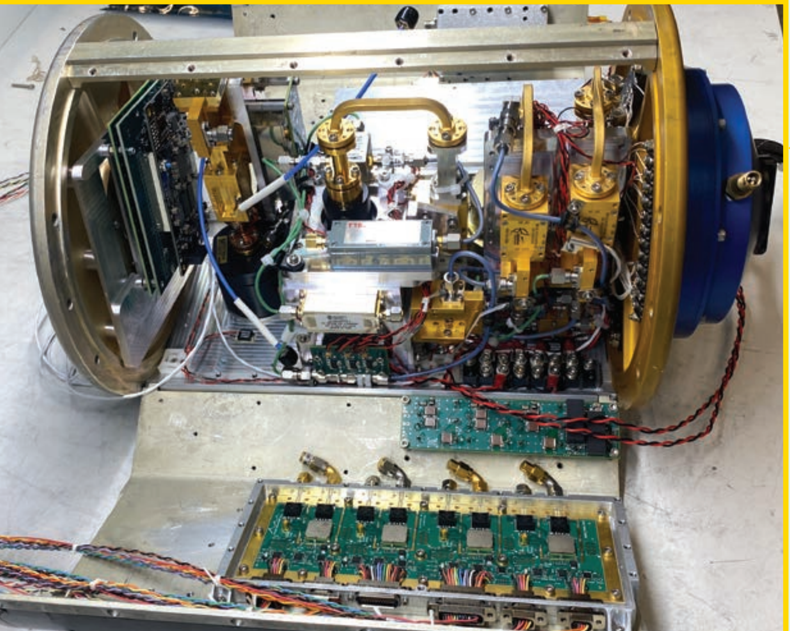
FireSense Technology seeks new, innovative Earth system observation capabilities to predict and manage wildfires and their impacts. ESTO's FireSense Technology program is a part of the broader Earth Science Division FireSense Program and works closely with NASA's Aeronautics Research Mission Directorate (ARMD), Space Technology Mission Directorate (STMD), and several interagency partners. FireSense Technology will leverage NASA resources to improve the end-to-end management of wildfires in the United States and around the world.

Over the next 4-5 years, FireSense will execute a series of airborne field campaigns to test novel technologies for assessing the impact of wildfires. These technologies will make use of broad capabilities in instrument and information technology, along with new observing platforms in space, in the air, and on the ground.

- **Hot Spot: High-Resolution Real-Time Wildfire Detection, Mapping, and Communication Relay System with Persistent Broad-Area Coverage** – Jared Leidich, Urban Sky
- **Sediment Plumes and Blooms: Using Earth Observations and Modeling to Forecast Post-Fire impacts to Reservoir Water Quality and Quantity** – Mary Miller, Michigan Technological University
- **Spaceflight Version of CFI** – Douglas Morton, NASA GSFC
- **Near real-time updated wildfire risk map model informed by powerline fault status** – Hamidreza Nazaripouya, Oklahoma State University
- **Wildland Fire Pre-Formulation Concept Study** – Rashmi Shah, NASA JPL

Decadal Survey Incubation

Decadal Survey Incubation (DSI) seeks to accelerate the readiness of two high-priority observables needing science-requirement refinement, technology development, and/or other advancements prior to cost effective flight implementation. 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.



7 Projects Active in FY23

DSI Project Highlight

This antenna prototype (shown below) from the "Deployable MetaLens for G-Band Earth Science Applications" project (PI: Richard Hodges, JPL) utilizes state-of-the-art design and fabrication techniques for millimeter-wave remote sensing. Such a MetaLens antenna could enable several PBL measurement concepts, including Differential Absorption Radar (DAR) and CloudCube, and be applicable to other commercial and military systems.

Credit: R. Kroodsma / NASA GSFC

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:

Earth System Digital Twins

These frameworks seek to 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.

Novel Observing Strategies

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.

Analytic Collaborative Frameworks

Once Earth observing missions are in operation, very large amounts of data are collected, often in differing formats and of diverse resolutions. Agile analytic frameworks enhance science investigations by fusing disparate datasets and pioneering visualization and analytics tools, including machine learning as well as relevant computing environments.

45 Projects Active in FY24

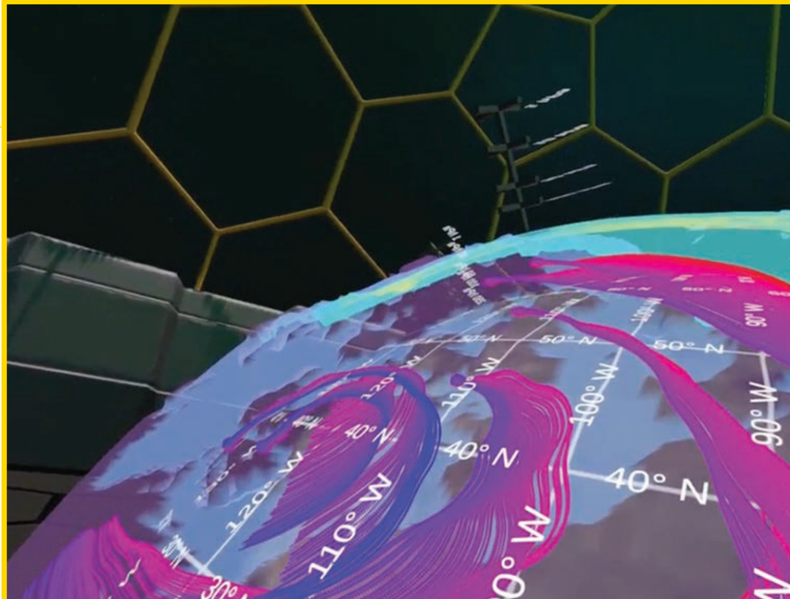
10 Projects Graduated ↓

- **A Path Towards Quantum-Computing-Assisted Earth Science Data Acquisition Tasking and Processing** – Shon Grabbe, NASA ARC
- **DTAS: A prototype Digital Twin of Air-Sea interactions** – Alison Gray, University of Washington
- **Stochastic parameterization of an atmospheric model assisted by quantum annealing** – Alexandre Guillaume, NASA JPL
- **Integrated Digital Earth Analysis System (IDEAS)** – Thomas Huang, NASA JPL
- **Transition of CAPRi (Cloud-based Analytical framework for Precipitation Research) to NASA Earth Information System (EIS)** – Sujay Kumar, NASA GSFC
- **An Intelligent Systems Approach to Measuring Surface Flow Velocities in River Channels** – Carl Legleiter, USGS
- **Development of the High Performance Version of GEOS-Chem (GCHP) to enable broad community access to high-resolution atmospheric chemistry modeling** – Randall Martin, Washington University in St Louis
- **D-SHIELD: Distributed Spacecraft with Heuristic Intelligence to Enable Logistical Decisions** – Sreeja Roy-Singh, NASA ARC
- **Coupled Statistics-Physics Guided Learning to Harness Heterogeneous Earth Data at Large Scales** – Yiqun Xie, University of Maryland
- **A formal study on Machine Learning (ML) and geospatial regression methods for processing Green House Gases (GHG) and air pollutants** – Chaowei (Phil) Yang, George Mason University

AIST Project Highlight

A screen capture from inside the Visualization And Lagrangian dynamics Immersive eXtended Reality Tool (VALIXR), a scientific exploration and analysis mixed reality tool developed at Goddard Space Flight Center for use with the Goddard Earth Observing System (GEOS) numerical weather prediction model. VALIXR is intended to help scientists identify, track, and understand the evolution of Earth science phenomena more quickly and intuitively – particularly atmospheric phenomena such as convective clouds, hurricanes, and smoke plumes that move within a 3-D flow field.

Credit: Credit: T. Grubb / NASA



FY24 PROGRAM UPDATES

Advanced Component Technology

Component and sub-system technologies are a principal driver of new instruments and measurement techniques. The Advanced Component Technology (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.

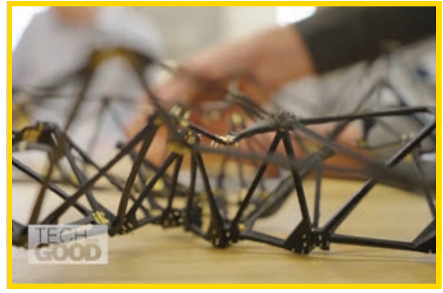
26 Projects Active in FY24

4 Projects Graduated in FY24

- **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 Laboratory
- **Integrated Receiver and Switch Technology (IRaST)** – William Deal, Northrop Grumman Corporation
- **Radar on a Chip** – Lute Maleki, OEWaves, Inc.

ACT Project Highlight

The Metalens Origami Deployable Lidar Telescope (MODeL-T), a project at Goddard Space Flight Center, was featured in a 7-minute Tech for Good CNN segment in early December 2023. The MODeL-T project is developing a 0.6 m collection aperture to a enable smaller, lighter, less expensive implementation of space-based lidar while improving measurement performance. The segment focused on the use of origami folding/deployment developed by project partners at Brigham Young University and addressed Earth science needs for lidar measurements. Other partners include Pennsylvania State University and MMA Design, LLC.



bitly

Credit: CNN

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.

36 Projects Active in FY24

13 Projects Graduated in FY24

- **Separated Thinned Array for Sensing of Ice Sheets (STASIS)** – Alexander Akins, NASA JPL
- **Quantum Gravity Gradiometry In Hybrid Architectures with Satellite-to-Satellite Tracking for Spaceborne Earth System Mass Change Measurements** – Srinivas Bettadpur, UT Austin
- **Metasurfaces for Compact, Next-Generation Polarimetric Remote Sensing of Aerosols and Clouds** – Federico Capasso, Harvard University
- **Black Array of Broadband Absolute Radiometers for Imaging Earth Radiation** – Odele Coddington, University of Colorado Boulder
- **Multi-Functional Lidar Measurements to Identify and Characterize Marine Debris using Time-Resolved Fluorescence** – Madeline Cowell, BAE Systems
- **Combining distributed RF and multi-spectral optical observations for a spaceborne 3-D lightning measurement concept** – Patrick Gatlin, NASA MSFC
- **Distributed Aperture Radar Tomographic Sensors (DARTS) to Map Three-Dimensional Vegetation Structure and Surface Topography** – Marco Lavalle, NASA JPL
- **MLSCube – A Microwave Limb Sounder for continuity of stratospheric observations in a 6U-CubeSat form factor** – Nathaniel Livesey, NASA JPL
- **Global L-band Active/Passive Observatory for Water Cycle Studies (GLOWS)** – David Long, BYU
- **Digitally Enhanced Meta-surface Radar/Radiometer for Snow Remote Sensing** – Hans-Peter Marshall, Boise State University
- **Tunable Light-guide Image Processing Snapshot Spectrometer (TuLIPSS) for Earth Science Research and Observation** – Tomasz Tkaczyk, Rice University
- **Multi-Spectral, Low-Mass, High-Resolution, Planar Integrated Photonic Imagers** – Ben Yoo, UC Davis
- **Signals of Opportunity Synthetic Aperture Radar for High Resolution Remote Sensing of Land Surfaces** – Simon Yueh, NASA JPL

IIP Project Highlight

The SToRM SAR (Satellite Tomography of Rain and Motion via Synthetic Aperture Radar) instrument completed ~20 hours of engineering and data-collection flights on NASA's Gulfstream V aircraft in June/July 2024, successfully observing rain in moderate and severe storms. A miniature, high resolution, multi-static Ku-band or X-Band radar, SToRM SAR represents a new approach to the special challenges of precipitation measurements, particularly for an eventual constellation of microsatellites that could make precipitation observations at the ~1 km horizontal resolution needed to characterize severe storm processes for weather research.

Credit: K Maschhoff / BAE Systems

Sustainable Land Imaging-Technology

8 Projects Active in FY24

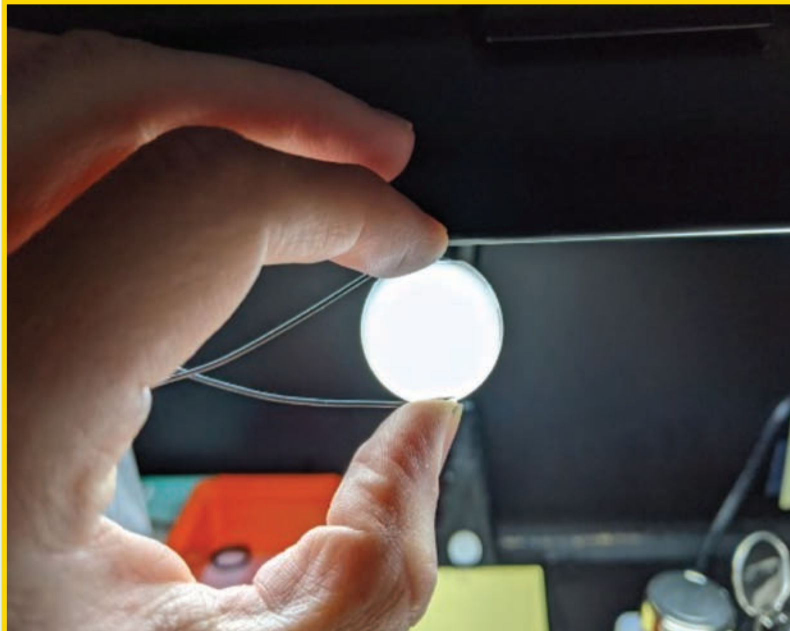
1 Project Graduated in FY24

- **Versatile Computational Pixel Infrared Land Imager** – David Ting, NASA JPL

For over 40 years, the Landsat series of satellites has been providing a continuous stream of moderate resolution, multi-spectral 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.

SLI-T Project Highlight

One aim of the SLI-T program is to develop novel methods for sensors to perform on-orbit calibration, particularly to reduce the size and mass of bulky calibration sub-systems. The TransCal project at BAE Systems is developing and testing Polymer Dispersed Liquid Crystal (PDLC) optical devices (an example shown here) for use as an in-path switchable calibration diffuser, switching from transparent and diffuse states.



Credit: N. Leisso / BAE Systems

Fighting Fire with AI

NASA's "Wildfire Digital Twin" project will equip firefighters and wildfire managers with a superior tool for monitoring wildfires, predicting harmful air pollution events, and helping researchers observe global wildfire trends more precisely.

The tool, developed with funding from ESTO and NASA's FireSense Program, will use artificial intelligence and machine learning to forecast potential burn paths in real time, merging data from in situ, airborne, and spaceborne sensors to produce global models with high precision.

Whereas current global models describing the spread of wildfires and smoke have a spatial resolution of about 10 kilometers per pixel, the Wildfire Digital Twin would produce regional ensemble models with a spatial resolution of 10-to-30 meters per pixel, an improvement of two orders of magnitude.

These models could be generated in a span of mere minutes. By comparison, current global models can take hours to produce.

Models with such high spatial resolution produced at this speed would be immensely valuable to first-responders and wildfire managers trying to observe and contain dynamic burns.

Milton Halem, a Professor of Computer Science and Electrical Engineering at the University of Maryland, Baltimore County, leads the Wildfire Digital Twin project, which includes a team of more than 20 researchers from six universities.

"We want to be able to provide firefighters with useful, timely information," said Halem, adding that in the field, "there is generally no internet, and no access to big supercomputers, but with our API version of the model, they could run the digital twin not just on a laptop, but even a tablet," he said.

NASA's FireSense program is focused on leveraging the agency's unique Earth science and technological capabilities to achieve improved wildfire management across the United States.

ESTO supports this effort within the program element, Technology Development for support of Wildfire Science, Management, and Disaster Mitigation (FireSense Technology), which is dedicated to developing novel observation capabilities for predicting and managing wildfires –including technologies like Earth System Digital Twins.

Earth System Digital Twins are dynamic software tools for modeling and forecasting climate events in real time. These tools rely on data sources distributed across multiple domains to create ensemble predictions describing everything from floods to severe weather.

In addition to assisting first responders, an Earth System Digital Twin dedicated to modeling wildfires would also be valuable to scientists monitoring wildfire trends globally. In particular, Halem hopes Wildfire Digital Twins will improve our ability to study wildfires across global boreal forests of cold-hardy conifers, which sequester vast amounts of carbon.

When these forests burn, all of that carbon is released back into the atmosphere. One study, released in August of 2023, found that boreal wildfires alone accounted for 25% of all global CO_2 emissions for that year to date.

"The reason CO_2 emissions from Boreal wildfires are taking place at an increasing yearly rate is because global warming is rising faster at high latitudes than the rest of the planet, and as a result, boreal summers there are becoming longer," said Halem.

"Whereas the rest of the planet may have warmed one degree Celsius since the pre-industrial revolution, this region has warmed well over two degrees."

Halem's work builds on other wildfire models, particularly the NASA-Unified Weather Research and Forecasting (NUWRF) model, developed by NASA, and WRF-SFIRE, developed by a team of researchers with support from the National Science Foundation. These models simulate phenomena like wind speed and cloud cover, which makes them the perfect foundation for a Wildfire Digital Twin.

Specifically, Halem's team is working on new satellite data assimilation techniques that will blend information from space-based remote sensors into their Wildfire Digital Twin, enabling improved global data forecasts that will be useful for emergencies and science missions alike.

In 2023, Halem's team participated in the first FireSense field campaign in collaboration with the National Forest Service's Fire and Smoke Model Evaluation Experiment (FASMEE) to observe smoke as it traveled more than 10 miles during a controlled burn in Utah, using a ceilometer. Now the team is feeding that data into their modeling software to help it track plumes more accurately.

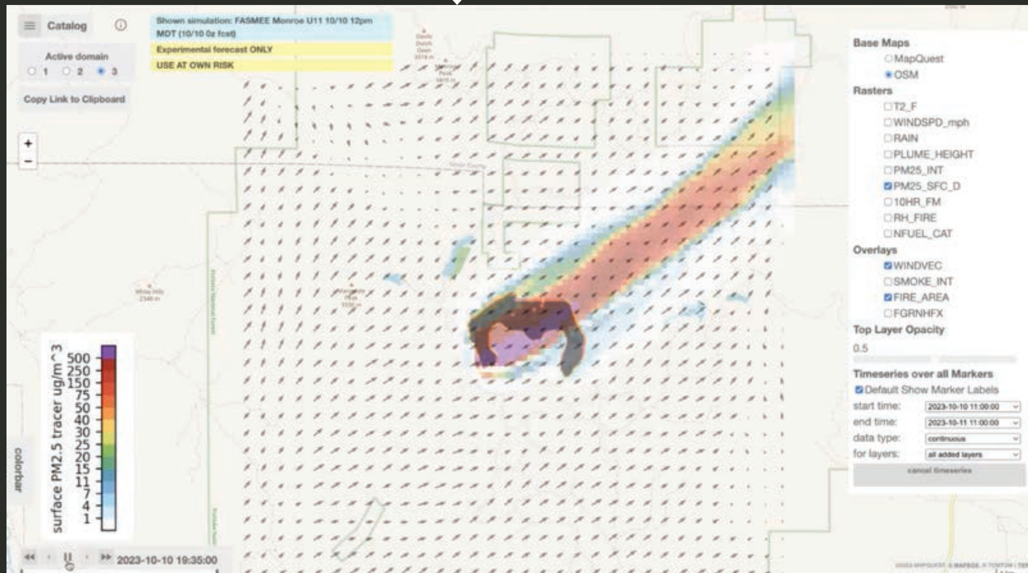
They're especially interested in tracking particles smaller than 2.5 micrometers, which are small enough to pass through a person's lungs and enter the bloodstream. These particles, also known as PM 2.5, can cause serious health issues even if a person is nowhere near an active burn.

"When these fires ignite and start to burn, they produce smoke, and this smoke travels considerable distances. It affects people not only locally, but also at distances of thousands of kilometers or more," said Halem.

Data from the controlled burn will also help Halem and his team quantify the relationship between aerosols and precipitation. Increased aerosols from wildfires have a huge impact on cloud formation, which in turn impacts how precipitation occurs downstream of an affected fire burn.

Assimilating all this information as it streams from sensors in real time is essential for detailing the full impact of wildfires at local, regional, and global scales.

A wildfire simulation describing the spread of PM 2.5 aerosols during a recent controlled burn, generated using the WRF-SFIRE model. "Wildfire Digital Twin" will build on this and other models to simulate active burns with unprecedented resolution. Credit: K. Clough / San Jose State University



Enabling PACE

It took the Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission just 13 minutes to reach low-Earth orbit from Cape Canaveral Space Force Station in February 2024. It took a network of scientists at NASA and research institutions around the world more than 20 years to carefully craft and test the novel instruments that allow PACE to study the ocean and atmosphere with unprecedented clarity.

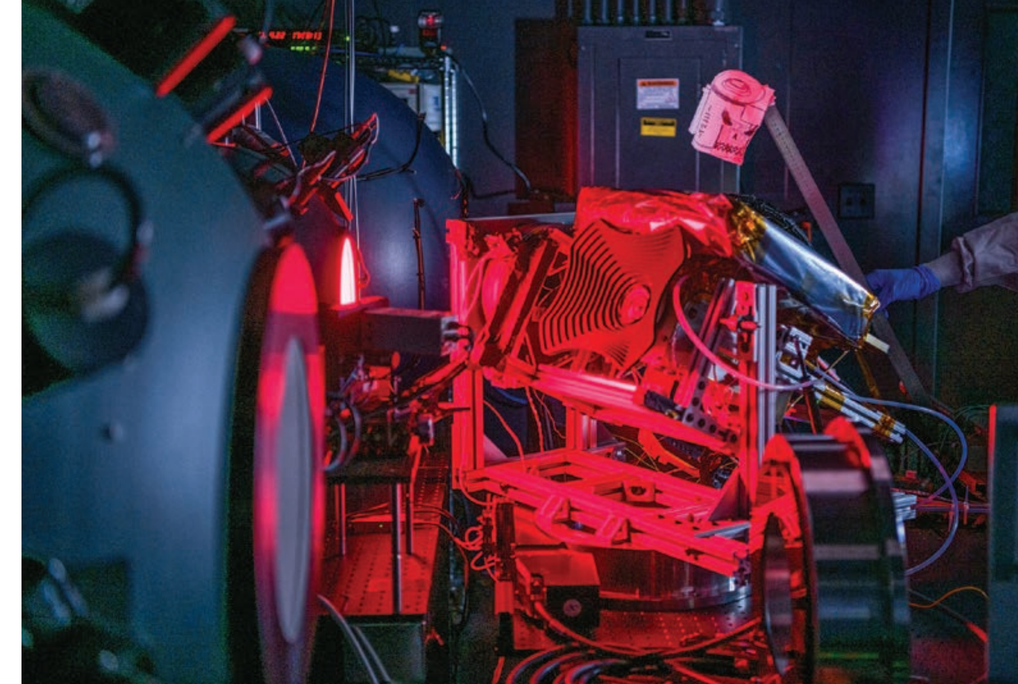
In the early 2000s, a team of scientists at NASA's Goddard Space Flight Center in Greenbelt, Maryland, prototyped the Ocean Radiometer for Carbon Assessment (ORCA) instrument, which ultimately became PACE's primary research tool: the Ocean Color instrument (OCI). Then, in the 2010s, a team from the University of Maryland, Baltimore County (UMBC), worked with NASA to prototype the Hyper Angular Rainbow Polarimeter (HARP), a shoebox-sized instrument that will collect groundbreaking measurements of atmospheric aerosols.

Neither PACE's OCI nor HARP2 — a nearly exact copy of the HARP prototype — would exist were it not for NASA's early investments in novel technologies for Earth observation through competitive grants distributed by ESTO. Over the last 25 years, ESTO has managed the development of more than 1,100 new technologies for gathering science measurements.

"All of this investment in the tech development early on basically made it much, much easier for us to build the observatory into what it is today," said Jeremy Werdell, an oceanographer at NASA Goddard and project scientist for PACE.

Charles "Chuck" McClain, who led the ORCA research team until his retirement in 2013, said NASA's commitment to technology development is a cornerstone of PACE's success. "Without ESTO, it wouldn't have happened. It was a long and winding road, getting to where we are today."

It was ORCA that first demonstrated a telescope rotating at a speed of six revolutions per second could synchronize perfectly with an array of charge-coupled devices — microchip-sized elements that transform telescopic projections into digital images. This innovation made it possible for OCI to observe hyperspectral shades of ocean color previously unobtainable using space-based sensors.



HARP2 undergoing calibration testing prior to launch aboard PACE. Credit: D. Henry / NASA

But what made ORCA especially appealing to PACE was its pedigree of thorough testing. "One really important consideration was technology readiness," said Gerhard Meister, who took over ORCA after McClain retired and serves as OCI instrument scientist. Compared to other ocean radiometer designs that were considered for PACE, "we had this proof-of-concept instrument, and we had shown that it would functionally work and that the technology was ready."

Technology readiness also made HARP an appealing solution to PACE's polarimeter challenge. Mission engineers needed an instrument powerful enough to ensure PACE's ocean color measurements weren't jeopardized by atmospheric interference, but compact enough to fly on the PACE observatory platform.

By the time Vanderlei Martins, an atmospheric scientist at UMBC, first spoke to Werdell about incorporating a version of HARP into PACE in 2016, he had proven the technology with AirHARP, an airplane-mounted version of HARP, and was using an ESTO award to prepare a HARP CubeSat for space.

HARP2 relies on the same optical system developed through AirHARP and HARP CubeSat. A wide-angle lens observes Earth's surface from up to 60 different viewing angles with a spatial resolution of 1.62 miles (2.6kilometers) per pixel, all without any moving parts. This gives researchers a global view of aerosols from a tiny instrument that consumes very little energy.

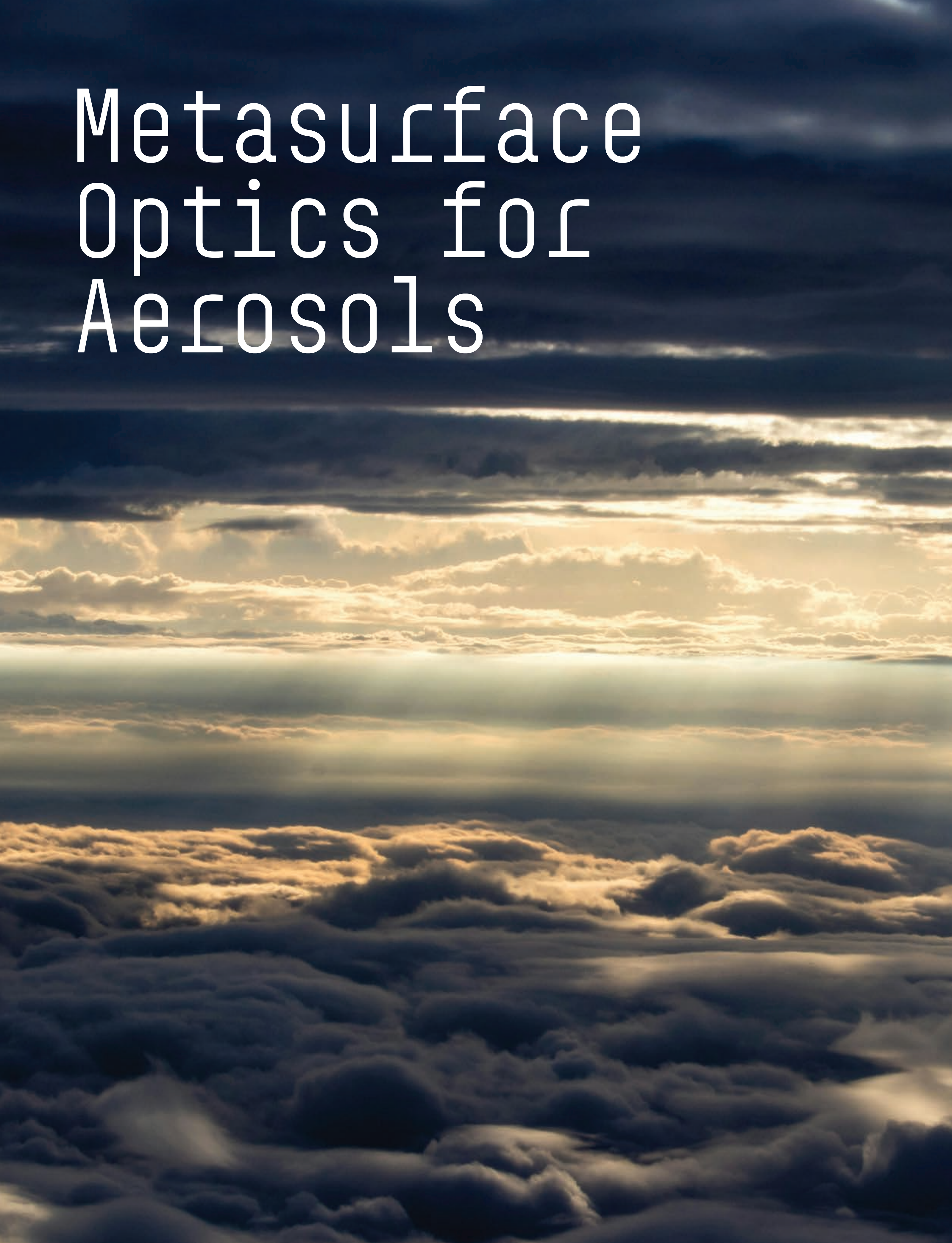
Were it not for NASA's early support of AirHARP and HARP CubeSat, said Martins, "I don't think we would have HARP2 today." He added: "We achieved every single goal, every single element, and that was because ESTO stayed with us."

That support continues making a difference to researchers like Jessie Turner, an oceanographer at the University of Connecticut who will use PACE to study algal blooms and water clarity in the Chesapeake Bay.

"For my application that I'm building for early adopters of PACE data, I actually think that polarimeters are going to be really useful because that's something we haven't fully done before for the ocean," Turner said. "Polarimetric data can actually help us see what kind of particles are in the water."

Without the early development and instrument test-drives, PACE as we know it wouldn't exist.

"It all kind of fell in place in a timely manner that allowed us to mature the instruments, along with the science, just in time for PACE," said McClain.



Metasurface Optics for Aerosols

Water droplets in burgeoning storm systems; particulates launched to the stratosphere by volcanic eruptions; ash from western wildfires drifting eastwards across the continental U.S. Aerosols such as these impact everything from severe weather to air quality. Polarimeters, which characterize aerosols and cloud particles by observing how they interact with light, are scientists' best tool for understanding the massive role these tiny particles play in atmospheric events.

But while there are many airborne polarimeters available to scientists, only a few of these instruments have ever flown in space. NASA's Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission, launched in 2024, marked the first space-based science mission featuring polarimetry in over a decade.

Kirk Knobelspiesse, an atmospheric scientist at NASA's Goddard Space Flight Center, explained that creating advanced polarimeters to study the atmosphere is essential for studying Earth's climate. "The composition of aerosols, the shape, the size – that's something that we really need to understand better to improve climate modeling," Knobelspiesse said.

A team of researchers from the Capasso Group at Harvard University, supported by ESTO, recently completed an early concept study exploring a new technology for space-based polarimetry. Specifically, the team investigated whether a novel polarization-sensitive metasurface optical element might be useful for observing atmospheric particles.

The study, which spawned papers in Optics Express and Applied Optics, concluded that this metasurface optical element can reliably detect polarized light within the 550, 670, and 870 nanometer wavelengths, ideal light signatures for observing aerosols and clouds particles.

"I think all of this will play well for the long-term plans of NASA," said Federico Capasso, Robert Wallace Professor of Applied Physics at Harvard and Principal Investigator for this project.

Traditional optics, like lenses in a telescope, rely on a material's bulk properties to control observed light. Metasurface optics, on the other hand, rely on complex arrays of micrometer-sized structures arranged across a flat surface. The spacing and shape of these structures determines how light interacts with a detector.

Also known as flat optics, metasurface optics are lighter and smaller than their traditional counterparts, making them less expensive to send into orbit. As NASA plans future Earth science missions, metasurface optics could be key to building a new generation of compact polarimeters.

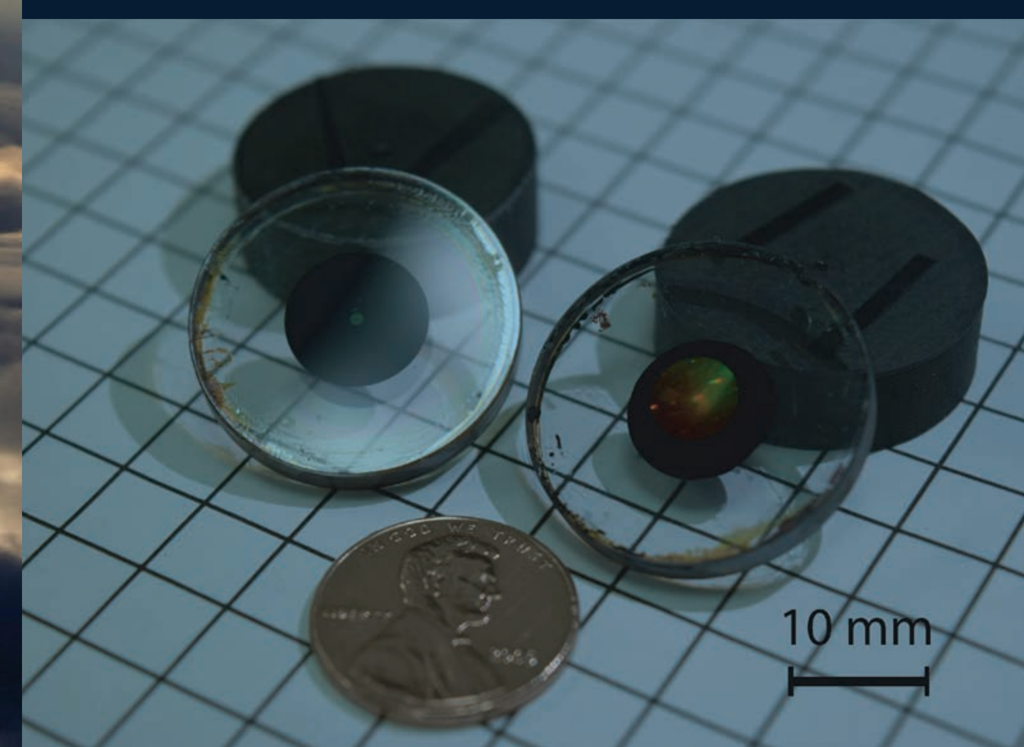
"The size, weight, and mass production possibility are often quoted as advantages for metasurface optics," said Lisa Li, a former member of the Capasso Group who played a key role in manufacturing this unique metasurface. Lighter, smaller components easily produced at scale can reduce the overall cost of a science mission.

Noah Rubin, another former member of the Capasso Group and a Co-Investigator for this project, explained that the key achievement of this project was proving that their metasurface could measure signatures of polarized light with the accuracy researchers would require from a science instrument.

But there were other promising results, too. While proving their metasurface was fit for science-grade polarimetry, the team found that their material may also allow researchers to incorporate an entire polarimetric system – a polarization sorter and a polarization imager – within a single optical structure.

"We realized it would be possible to make, essentially, what we call a flat polarimeter," said Rubin.

There is still much work to be done before NASA has a flight-ready metasurface polarimeter at its disposal, but, Rubin said, this early work sponsored by ESTO's Instrument Incubator Program produced a scientific bedrock on which future metasurface breakthroughs will rely. "I'd like to extend some of this work, some of this polarization sensitive imaging, to include infrared light, which is a very important wavelength regime for ice cloud remote sensing," he said.



Photograph of two fully fabricated flat polarimeter samples. Credit: Capasso Group

Playing 3D-CHESS

Each day, sensors scattered across Earth's surface, dispersed throughout Earth's atmosphere, and situated within Earth's orbit produce torrents of scientific data, supplying researchers with more information about our world than humans have ever had before.

But quick as they are to communicate their observations with scientists, these sensors rarely communicate with one another. Each individual instrument operates in its own silo, making it difficult to orchestrate campaigns that include sensors from multiple domains.

"When it comes to Earth observation satellites and missions, the architectures are still very simple," said Daniel Selva, an Associate Professor of Aerospace Engineering at the University of Texas, A&M. "There's not a whole lot of onboard data processing or decision making or coordination amongst satellites in a constellation."

Selva and a team of researchers are working with ESTO to change that. Their project, "Decentralized, Distributed, Dynamic, and Context Aware Heterogeneous Sensor Systems" (3D-CHESS) would allow sensors to coordinate with each other more effectively and operate with greater autonomy, uniting disparate instruments within a single, dynamic sensor web.

"The idea of a sensor web is basically to turn that static, silo-based architecture into something that looks a lot more like a dynamic network of sensors," said Selva.

This dynamic network would make it easier to observe rapidly-changing features of Earth's environment, such as harmful algal blooms and severe weather.

Sensor webs – collections of heterogeneous sensors focused on the same task – have been around since the late 1990s, but autonomous sensor webs, like 3D-CHESS, are new.

Rather than using a human operator to organize sensor networks, 3D-CHESS would equip sensors with the intelligence they need to organize themselves with minimal human guidance. Each sensor would understand not only its own capabilities, but the capabilities of other sensors within a network.

This context-aware autonomy would make it possible, for example, for an airborne sensor to detect an event, request additional observations from space-based sensors, and then work with the space-based sensors to determine which instrument is best suited to study the event in greater detail.

In addition, rather than having a central node organizing the entire network, 3D-CHESS would use decentralized task algorithms to allow sensor webs to form and dissolve according to the observational needs of the moment.

"The idea is that sensors bid for a task based on how well they think they can perform the task and how much it is going to 'cost' them – in terms of energy, for example, to do it. They communicate with one another to exchange these bids and whoever has the highest bid, performs the task," said Selva.

This means that sensors maintained by different companies and government agencies could collaborate temporarily before returning to their primary missions.

"You're really trying to get to the point where you don't rely on the human operator to say, 'react to an event of interest,'" explained Selva. "You don't have to rely on human operators to decide who does what, which is what we do today."

Instead, Selva said, instruments can use a shared reference to organize an optimal observation network on their own. This shared reference, the knowledge graph, is a key technology innovation.

"You can think of it as a database, but instead of looking like a spreadsheet or something like that, it looks like a big graph," said Selva. The nodes and edges on the graph, he explained, are "all about what types of sensor can measure what things, and which satellites carry which types of sensors."

Another key technology innovation will be the inference algorithms sensors use to query the knowledge graph. These algorithms help sensors answer deterministic, yes-or-no questions, as well as probabilistic, 'how likely is this even to occur' questions.

"You can ask questions to the knowledge graph, 'Can I perform this task' or 'Is thermal infrared radiance related to temperature,' right? You can query the knowledge graph, and get answers with probabilities," said Selva.

3D-CHESS is a proof-of-concept project to determine if this approach is viable. To do this, Selva and his team developed a simulation that they'll use to prototype an effective knowledge graph and a collection of task allocation algorithms.

Ultimately, their goal is to produce an accessible software tool that scientists from numerous Earth science disciplines can use to achieve ambitious research goals.

"By the end of this project, we are going to release an open source tool that is meant to be quite flexible, something that other researchers can use to try to figure out if an autonomous sensor web is a feasible and appealing approach for a given application," said Selva.

An image from NASA's MODIS instrument depicting an algal bloom (green) in the Florida Keys. With 3D-CHESS, researchers would be able to study algal blooms and other fast-changing events more effectively. Credit: NASA

Fusing Land Data

Earth's cryosphere changes slowly. Ice sheets, glaciers, and perennial snowfields form and fade away over centuries or even millennia, dramatically altering entire continents in the process.

But as climate change continues to raise global temperatures, these frosty formations are disappearing at an unprecedented rate. Since 2002, Antarctica alone has lost more than 140 billion tons of ice annually.

Humans the world over feel the impact of this rapid ice loss. NASA estimates that meltwater from ice sheets is responsible for about one-third of the global average rise in sea level since 1993.

"We need current, accurate measurements for the coastline of the United States, and the world, really, to understand the impacts of sea level rise and flooding moving forward into the next century," said David Shean, an Assistant Professor of Civil and Environmental Engineering at the University of Washington, Seattle.

Shean and a team of researchers from University of Washington, NASA's Goddard Space Flight Center, and NASA's Ames Research Center, are developing new software tools that will help researchers study Earth's surface with unprecedented accuracy.

Their project, "Advanced Information Systems to Fill STV Gaps: Next-generation Stereo and Lidar fusion and Sensor Technology," will equip researchers with a collection of open-source algorithms to automatically fuse satellite lidar and stereo photogrammetry data, dramatically increasing the quality of Earth surface topography and vegetation (STV) measurements.

The 2017 Earth Decadal Survey, produced by the National Academy of Science, identified STV as an Incubation Targeted Observable – a subject worthy of high-priority technology investments in preparation for a full science mission within the next decade.

Shean's work directly addresses this key recommendation, laying the foundation for future NASA missions dedicated to monitoring Earth's surface topography and vegetation from space.

"That's really what this incubation project is about: maturing the technologies, developing the workflows to generate the data products we're going to need, and then trying to figure out the requirements moving forward as we go into the actual instrument design," said Shean.

Stereo photogrammetry uses multiple photos taken at different angles to reconstruct the 3D shape of objects, while lidar uses pulsed lasers to make sparse 3D measurements with cm-scale accuracy.

Each of these remote sensing techniques can generate detailed models of the Earth's surface, but merging both types of data makes it easier to produce more accurate measurements of Earth's surface at a global scale.

Those measurements will help Shean and his team accomplish another technology goal: to develop algorithms for a 'ground tracker,' a new satellite subsystem that will improve the pointing accuracy of both stereo and LiDAR measurements by an order of magnitude using features on the planet's surface, like boulders or shrubs, as reference points.

To accomplish their work, Shean and his team will perform simulations for different instrument configurations and develop machine learning models to fuse the disparate stereo and lidar data sets automatically.

In addition, these algorithms will help researchers mitigate errors and artifacts caused by subtle satellite vibrations in existing stereo data sets.

"Satellites are always vibrating very, very slightly while collecting data, which introduces pointing error" said Shean. "We're trying to a build user-friendly software and routines to correct these tiny vibrations in archived stereo images from the last 20 years for many really important places on the earth, so we can measure change with decimeter – 10 cm – accuracy."

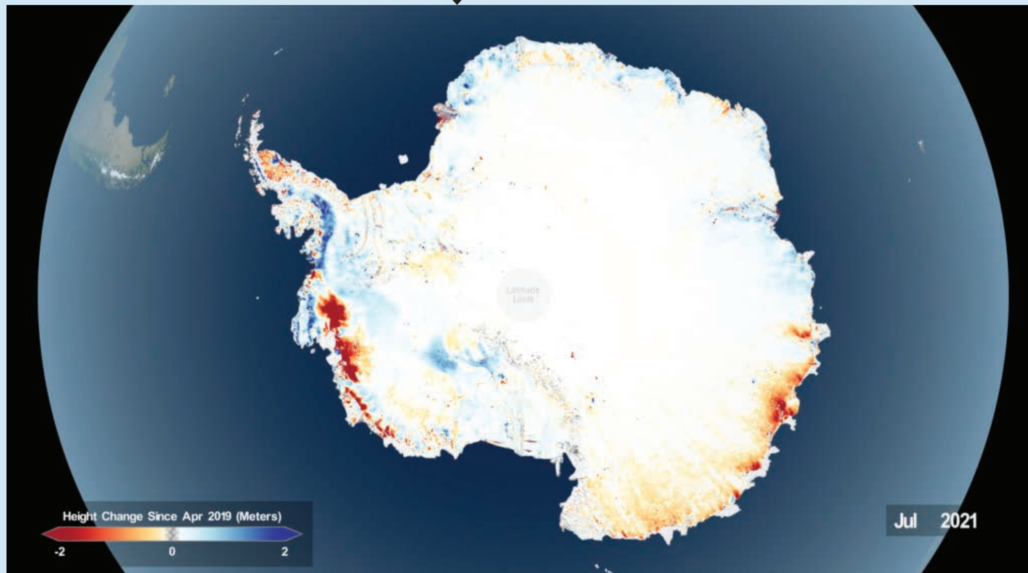
These correction algorithms and the new instrument subsystem could also have applications beyond Earth. Planetary scientists studying the surfaces of other rocky or icy planets might use them to map worlds around our solar system and beyond.

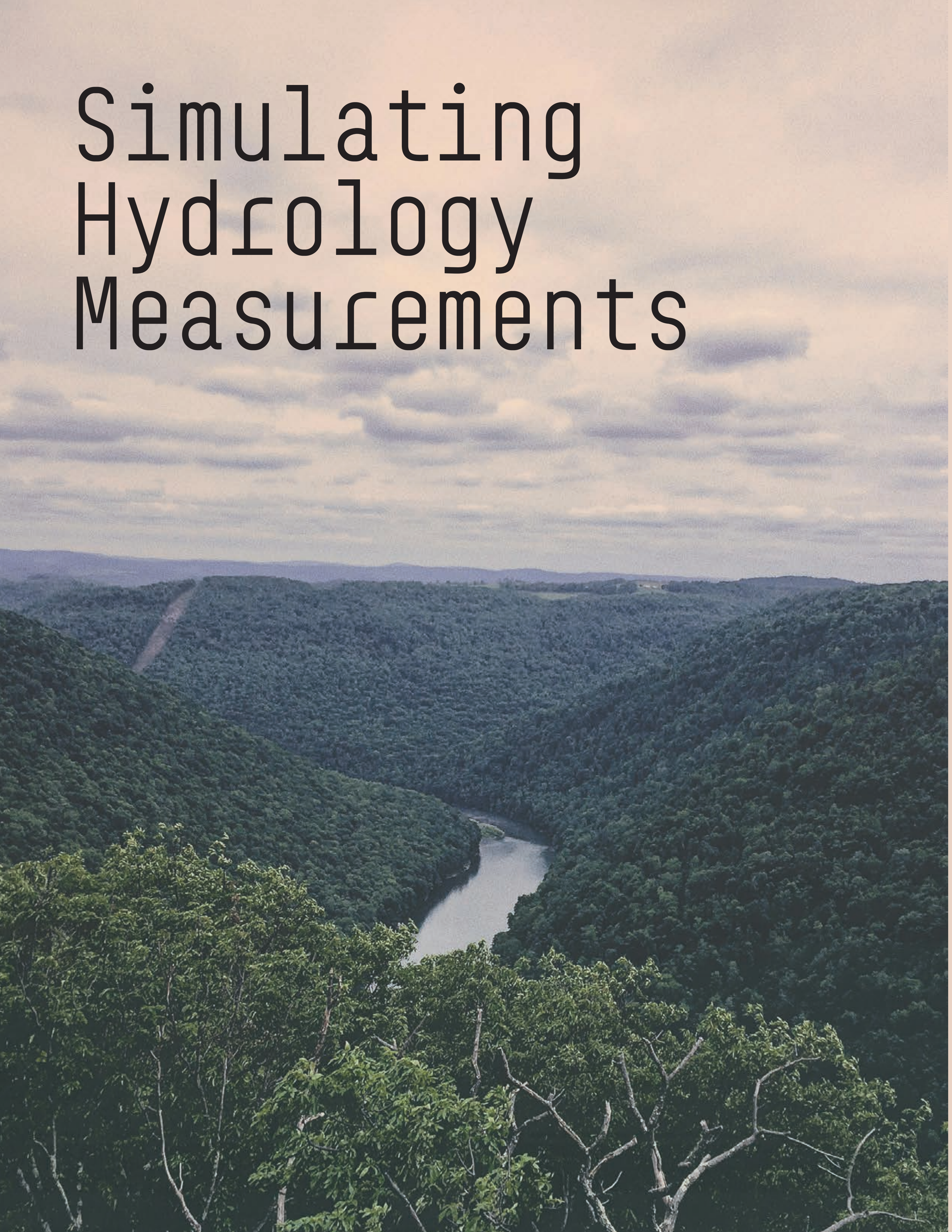
"The technology we're trying to develop here, this precise pointing algorithm, this 'ground tracker,' that should work on Mars too, and it should enable us to make much more accurate measurements of the Martian surface," said Shean.

But Shean is most concerned with advancing our understanding of Earth's rapidly changing surface, and how those changes might impact current and future generations.

"I want to apply my skills to work on something that matters for the eight billion people here on Earth right now," said Shean. "I moved on from Mars research because I wanted to do something that mattered here, to understand what's happening to our glaciers and ice here on Earth."

Satellite imagery from NASA's IceSAT-2 instrument shows Antarctic ice melt since April 2019. A new data fusion project will make it easier for researchers to observe Earth's topography and track phenomena like shrinking glaciers. Credit: NASA





Simulating Hydrology Measurements

From radar instruments smaller than a shoebox to radiometers the size of a milk carton, there are more tools available to scientists today for observing complex Earth systems than ever before. But this abundance of available sensors creates its own unique challenge: how can researchers organize these diverse instruments in the most efficient way for field campaigns and science missions?

To help researchers maximize the value of science missions, Bart Forman, an Associate Professor in Civil and Environmental Engineering at the University of Maryland, and a team of researchers from the Stevens Institute of Technology and NASA's Goddard Space Flight Center, prototyped an Observational System Simulation Experiment (OSSE) for designing science missions dedicated to monitoring terrestrial freshwater storage.

"You have different sensor types. You have radars, you have radiometers, you have lidars – each is measuring different components of the electromagnetic spectrum," Forman said. "Different observations have different strengths."

Terrestrial freshwater storage describes the integrated sum of freshwater spread across Earth's snow, soil moisture, vegetation canopy, surface water impoundments, and groundwater. It's a dynamic system, one that defies traditional, static systems of scientific observation.

Forman's project builds on prior technology advancements he achieved during an earlier ESTO project in which he developed an observation system simulation experiment for mapping terrestrial snow.

It also relies heavily on innovations pioneered by NASA's Land Information System (LIS) and NASA's Trade-space Analysis Tool for Designing Constellations (TAT-C), two modeling tools that began as ESTO investments and quickly became staples within the Earth science community.

Forman's tool incorporates these modeling programs into a new system that provides researchers with a customizable platform for planning dynamic observation missions that include a diverse collection of spaceborne data sets.

In addition, Forman's tool also includes a "dollars-to-science" cost estimate tool that allows researchers to assess the financial risks associated with a proposed mission.

Together, all of these features provide scientists with the ability to link observations, data assimilation, uncertainty estimation, and physical models within a single, integrated framework.

"We were taking a land surface model and trying to merge it with different space-based measurements of snow, soil moisture, and groundwater to see if there was an optimal combination to give us the most bang for our scientific buck," explained Forman.

While Forman's tool isn't the first information system dedicated to science mission design, it does include a number of novel features. In particular, its ability to integrate observations from spaceborne passive optical radiometers, passive microwave radiometers, and radar sources marks a significant technology advancement.

Forman explained that while these indirect observations of freshwater include valuable information for quantifying freshwater, they also each contain their own unique error characteristics that must be carefully integrated with a land surface model in order to provide estimates of geophysical variables that scientists care most about.

Forman's software also combines LIS and TAT-C within a single software framework, extending the capabilities of both systems to create superior descriptions of global terrestrial hydrology.

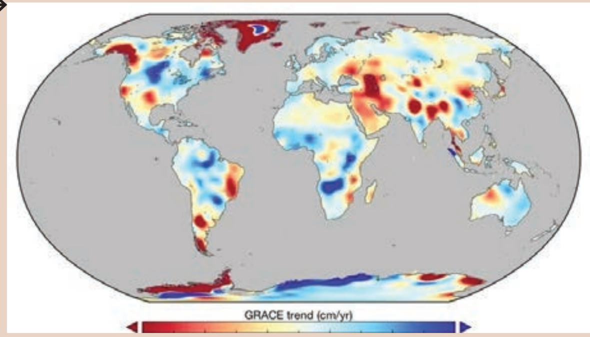
Indeed, Forman stressed the importance of having a large, diverse team that features experts from across the Earth science and modeling communities.

"It's nice to be part of a big team because these are big problems, and I don't know the answers myself. I need to find a lot of people that know a lot more than I do and get them to sort of jump in and roll their sleeves up and help us. And they did," said Forman.

Having created an observation system simulation experiment capable of incorporating dynamic, space-based observations into mission planning models, Forman and his team hope that future researchers will build on their work to create an even better mission modeling program.

For example, while Forman and his team focused on generating mission plans for existing sensors, an expanded version of their software could help researchers determine how they might use future sensors to gather new data.

"With the kinds of things that TAT-C can do, we can create hypothetical sensors. What if we double the swath width? If it could see twice as much space, does that give us more information? Simultaneously, we can ask questions about the impact of different error characteristics for each of these hypothetical sensors and explore the corresponding tradeoff." said Forman.



Satellite imagery from NASA's IceSAT-2 instrument shows Antarctic ice melt since April 2019. A new data fusion project will make it easier for researchers to observe Earth's topography and track phenomena like shrinking glaciers. Credit: NASA

Mapping Snow

Summer heat has significant effects in the mountainous regions of the western United States: melted snow rushes from snowy peaks into the rivers, reservoirs, and streams that supply millions of Americans with freshwater—as much as 75% of some states' annual freshwater supply.

But as climate change brings winter temperatures to new highs, these summer rushes of freshwater slow to a trickle. Warmer winters means less snowfall in the mountains, which leads to smaller snowpacks and, ultimately, less snowmelt available to communities across the West.

"The runoff supports cities most people wouldn't expect," explained Chris Derksen, a glaciologist and Research Scientist with Environment and Climate Change Canada. "Big cities like San Francisco and Los Angeles get water from snowmelt."

To forecast snowmelt with greater accuracy, ESTO and a team of researchers from the University of Massachusetts, Amherst, are developing SNOWWI, a dual-frequency, synthetic aperture radar that could one day be the cornerstone of future science missions measuring snow mass on a global scale – something the science community lacks.

SNOWWI aims to fill this technology gap. In January and March, 2024, the SNOWWI research team passed a key milestone, flying their prototype for the first time aboard a small, twin-engine aircraft in Grand Mesa, Colorado, and gathering useful data on the area's winter snowfields.

"I'd say the big development is that we've gone from pieces of hardware in a lab to something that makes meaningful data," explained Paul Siqueira, Professor of Engineering at the University of Massachusetts, Amherst, and Principal Investigator for SNOWWI.

SNOWWI stands for "Snow Water-equivalent Wide Swath Interferometer and Scatterometer." The instrument probes snowpacks with two Ku-band radar signals: a high-frequency signal that interacts with individual snow grains, and a low-frequency signal that passes through a snowpack to the ground.

The high-frequency signal gives researchers a clear look at the consistency of a snowpack, while the low-frequency signal helps researchers determine a snowpack's total depth.

"Having two frequencies allows us to better separate the influence of the snow microstructure from the influence of the snow depth," said Derksen, who participated in the Grand Mesa field campaign. "One frequency is good, two frequencies is better."

As both of those scattered signals interact with the snowpack and bounce back towards the instrument, they lose energy. SNOWWI measures that lost energy, and researchers later correlate those losses to features within the snowpack, especially its depth, density, and mass.

From an airborne platform with an altitude of 4 kilometers (2.5 miles), SNOWWI could map 100 square kilometers (38 square miles) of snowy terrain in just 30 minutes. From space, SNOWWI's coverage would be even greater. Siqueira is working with Capella Space to develop a space-ready SNOWWI for satellite missions.

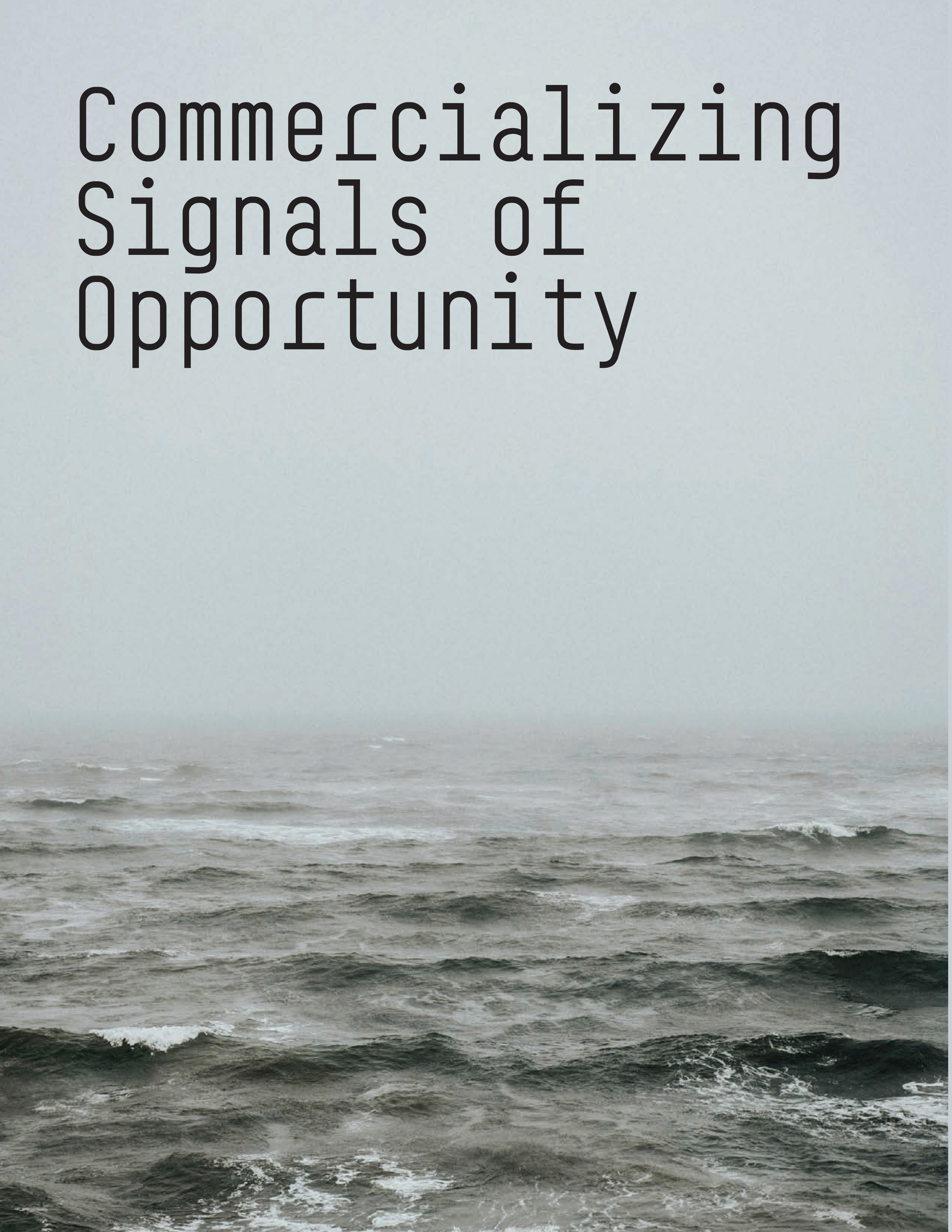
But there's still much work to be done before SNOWWI visits space. Siqueira plans to execute another field campaign, this time in the mountains of Idaho. Grand Mesa is relatively flat, and Siqueira wants to see how well SNOWWI can measure snowpacks tucked in the folds of complex, asymmetrical terrain.

For Derksen, who spends much of his time quantifying the freshwater content of snowpacks in Canada, having a reliable database of global snowpack measurements would be game-changing.

"Snowmelt is money. It has intrinsic economic value," he said. "If you want your salmon to run in mountain streams in the spring, you must have snowmelt. But unlike other natural resources, at this time, we really can't monitor it very well."

The SNOWWI team in Grand Mesa, preparing to flight test their instrument. From an altitude of 4 kilometers (2.5 miles), SNOWWI can map 100 square kilometers (about 38 square miles) in just 30 minutes. Credit: Paul Siqueira

Commercializing Signals of Opportunity



A science antenna developed with support from ESTO is now in low-Earth orbit aboard MuSat2, a commercial remote-sensing satellite flown by the aerospace company Muon Space. The dual-frequency science antenna was originally developed as part of the Next Generation GNSS Bistatic Radar Instrument (NGRx). Aboard MuSat2, it will help measure ocean surface wind speed—an essential data point for scientists trying to forecast how severe a burgeoning hurricane will become.

"We're very interested in adopting this technology and pushing it forward, both from a technology perspective and a product perspective," said Jonathan Dyer, CEO of Muon.

Using this antenna, MuSat2 will gather signals transmitted by navigation satellites as they scatter off Earth's surface and back into space. By recording how those scattered navigation signals change as they interact with Earth's surface, MuSat2 will provide meteorologists with data points they can use to study severe weather.

"We use the standard GPS signals you know—the navigation signals that work for your car and your cell phone," explained Chris Ruf, director of the University of Michigan Space Institute and principal investigator for NGRx.

Ruf designed the entire NGRx system to be an updated version of the sensors on NASA's Cyclone Global Navigation Satellite System (CYGNSS), another technology he developed with support from ESTO. Since 2016, data from CYGNSS has been a critical resource for people dedicated to forecasting hurricanes.

The science antenna aboard MuSat2 enables two key improvements to the original CYGNSS design. First, the antenna allows MuSat2 to gather measurements from satellites outside the U.S.-based GPS system, such as the European Space Agency's Galileo satellites. This capability enables MuSat2 to collect more data as it orbits Earth, improving its assessments of conditions on the planet's surface.

Second, whereas CYGNSS only collected cross-polar radar signals, the updated science antenna also collects co-polar radar signals. This additional information could provide improved information about soil moisture, sea ice, and vegetation.

"There's a whole lot of science value in looking at both polarization components scattering from the Earth's surface. You can separate apart the effects of vegetation from the effects of surface, itself," explained Ruf.

For Muon Space, this technology infusion has been helpful to the company's business and science missions. Dallas Masters, Vice President of Muon's Signals of Opportunity Program, explains that NASA's investments in NGRx technology made it much easier to produce a viable commercial remote sensing satellite. According to Masters, "NGRx-derived technology allowed us to start planning a flight mission early in our company's existence, based around a payload we knew had flight heritage."

Dyer agrees. "The fact that ESTO proves out these measurement approaches – the technology and the instrument, the science that you can actually derive, the products from that instrument – is a huge enabler for companies like ours, because we can adopt it knowing that much of the physics risk has been retired," he said.

Ultimately, this advanced antenna technology for measuring ocean surface wind speed will make it easier for researchers to turn raw data into actionable science products and to develop more accurate forecasts.

"Information is absolutely precious. When it comes to forecast models and trying to understand what's about to happen, you have to have as good an idea as you can of what's already happening in the real world," said oceanographer Lew Gramer, an Associate Scientist with the Cooperative Institute for Marine and Atmospheric Studies and NOAA's Hurricane Research Division.

MuSat2 at Vandenberg Air Force Base, prior to launch. MuSat2 leverages a dual-frequency science antenna developed with support from NASA to measure phenomena such as ocean wind speed. Credit: Muon Space

Building A Thinner Spectrometer

A NASA-funded metamaterial optical filter could become the cornerstone of new sensors and spectral cameras for observing atmospheric composition, which are critical tools for improving weather, air quality, and climate models.

Igor Bendoym, Lead Design Engineer at Phoebus Optoelectronics and Principal Investigator for this project, explained that he and his team created a novel metamaterial that can detect multiple light signatures reflected by atmospheric aerosols and gases.

It's an ideal component for compact, cost-efficient spectrometers, and those instruments are key to characterizing trace gases, aerosols, water vapor, and industrial pollutants on a global scale.

Traditional spectrometers rely on complex optical subsystems to target specific wavelengths of light for observation. Bendoym's metamaterial optical filter, which is thinner than a grain of sand, allows researchers to eliminate those bulky subsystems without compromising the quality of gathered data.

"Using the metamaterial, we can remove most of the optics within the spectrometer, measuring only the spectral channels needed and miniaturize the entire system because we can eliminate most pre-processing of the light signal. The metamaterial allows the direct filtering of the collected, focused light, eliminating the need for bulky collimating and dispersing optics," said Bendoym.

Metamaterials are synthetic materials specifically engineered to exhibit electromagnetic qualities and properties that are hard to find in naturally occurring materials. They are a promising technology for solving a host of scientific problems, from remote sensing to laser communications.

"What metamaterials provide for us scientists, engineers, and humanity, is really what I'd like to describe as a chest of light-controlling tools that we can deploy in whatever way an application requires," said David Crouse, founder of Phoebus Optoelectronics and Professor of Electrical and Computer Engineering at Clarkson University.

Bendoym and his team created a metamaterial design that includes carefully engineered arrays of resonators located within stacks of thin semiconductor layers. The exact geometry and configuration of the resonators can be changed across the chip so that only the targeted gases and aerosols are observed.

"We wanted to design metamaterial structures that can be made using conventional fabrication techniques such that the path to high volume manufacturing and commercialization is easier, " said Crouse.

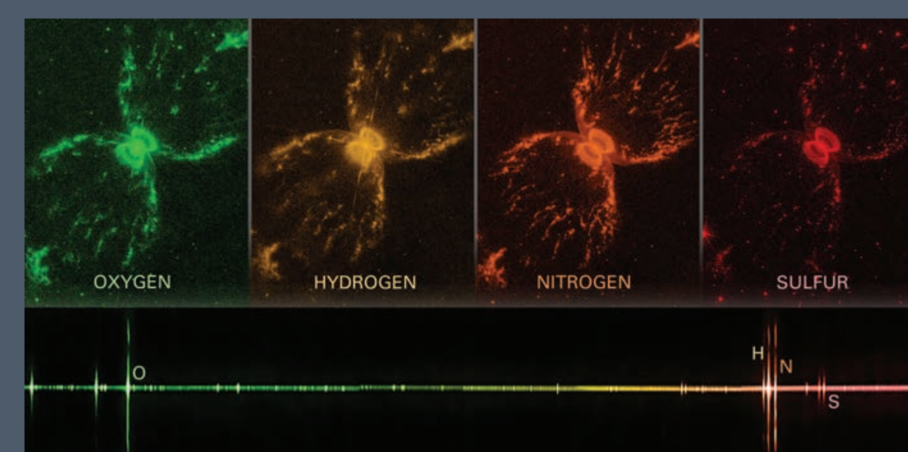
Having developed and demonstrated the utility of their metamaterial for airborne and spaceborne spectroscopy with a grant from ESTO's Advanced Component Technology program, Bendoym and his team are currently working with ESTO's Instrument Incubator Program, along with researchers at Atmospheric & Environmental Research, Inc. (AER) and BAE Systems, to develop a complete miniaturized spectrometer prototype for the measurement of boundary layer temperature and water vapor profiles.

From there, Bendoym and his team hope to work with NASA and private companies to incorporate their miniaturized spectrometer onboard spaceborne and airborne platforms. These might include CubeSats situated in low-Earth orbit or small, unmanned aerial vehicles flying through Earth's atmosphere.

Their metamaterial optical filter could even find its way into applications beyond planet Earth. Bendoym and his team are collaborating with AER and BAE Systems to see whether their metamaterial might help researchers gather better images of distant stars, planets, and other interstellar objects.

"We want to work with our industry and government partners to make products that, at the end of the day, will benefit humanity to the widest extent possible," said Crouse.

The Cornell University Nanoscale Science and Technology Facility, the Harvard University Center for Nanoscale Systems, and the Clarkson University Center for Advanced Materials Processing helped Bendoym's research team fabricate and test its metamaterials.



Spectroscopy allows researchers to detect specific chemicals by measuring the kinds of light those chemicals emit. ESTO's novel metamaterial optical filter will make it easier for scientists to build compact, lightweight spectrometers for Earth observation. Credit: NASA, ESA, and J. DePasquele

The Future of FireSense

ESTO's FireSense Technology Program welcomed three new projects into its portfolio this year, driving NASA's mission to address major challenges in wildfire management another step forward.

Each of these three projects focuses on a different aspect of wildfire management. They include a balloon-based observing system for detecting and monitoring active burns, AI-driven models for preventing wildfires caused by powerlines, and an online database for forecasting how long it will take bodies of freshwater ruined by burns to become clean and fit for human consumption again.

But ultimately, these unique projects, along with each of the other projects in ESTO's FireSense Technology portfolio, complement one another, setting the stage for a new era of effective wildfire mitigation.

Sediment Plumes and Blooms

To help mitigate damage to freshwater resources caused by wildfires, a team of scientists and engineers from Michigan Technological University (MTU) will create WaterScars Watch, an online database for forecasting harmful algal blooms caused by erosion from wildfires.

WaterScars Watch unites NASA remote-sensors and hydrological models originally produced to forecast harmful algal blooms in the great lakes within a single, user-friendly interface to help watershed managers assess how water resources will fare in a post-burn environment.

"With this increased runoff of nutrients into western watersheds that have reservoirs, there's a lot of concern that they're going to have more harmful algal blooms," said Mary Miller, a Research Engineer at MTU and Principal Investigator for WaterScars Watch.

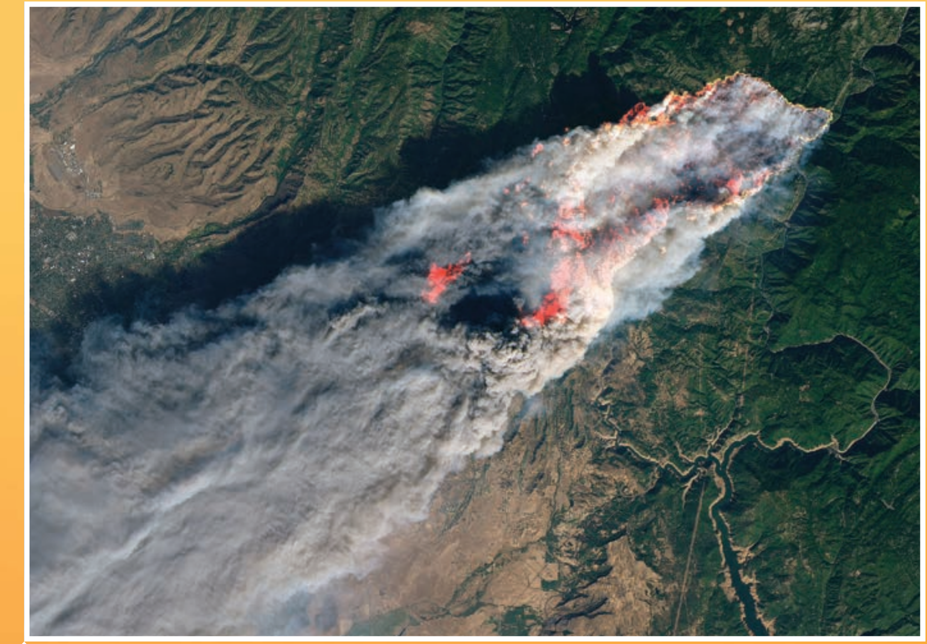
An algal bloom in Lake Erie. WaterScars Watch modifies algorithms used to forecast harmful algal blooms in the Great Lakes to mitigate damage to freshwater resources caused by runoff after a wildfire. Credit: NASA

Near real-time updated wildfire risk map model informed by powerline fault status

To help prevent wildfires caused by powerline faults, a team of researchers from Oklahoma State University will develop AI-driven models for estimating the probability of fire ignition from electrical faults in powerlines.

Led by Hamidreza Nazaripouya, assistant professor and Distinguished Fellow of Electrical and Computer Engineering at Oklahoma State University, the project will feature a comprehensive database on the dynamics of electrical faults, which will then inform an AI-based powerline situational awareness tool for estimating ignition probabilities.

"The studies and statistics show that powerlines regularly rank among the top identified causes of wildfires," said Nazaripouya, "That is what motivated me to study this problem, as a power systems engineer."



The 2018 Camp Fire–which was the most destructive in California's history–was ignited by a faulty powerline. Credit: NASA / Landsat

An Urban Sky technician deploys a balloon-based sensor from the bed of a pickup truck. Credit: Urban Sky

Hot Spot

To observe active burns and detect burgeoning wildfires more effectively, engineers and researchers at the aerospace company Urban Sky, Inc., will develop a balloon-based surveillance and communications system.

Dubbed "Hot Spot," the project uses high-altitude balloons to solve two pressing problems facing wildfire managers: first, the need for high-resolution observations of active and nascent wildfires; second, the need to share those observations with first responders located far from reliable broadband coverage.

"Through this communications hub, we'll enable web-connected communication, but also direct communication to firefighters in the field, so they can see the data that's being generated with our system," explained Jared Leidich, co-founder and Chief Technology Officer at Urban Sky Theory.

Tech Demos On Orbit

ESTO's InVEST program validates new technologies in the harsh environment of space. The program aims to reduce the overall risk of incorporating new technologies into future Earth science missions. Recent advancements in small, standardized satellites and low-cost access to space have transformed the way technologies are demonstrated and validated. Meaningful risk reduction for hardware components and information systems can be accomplished quickly for future flight instruments. Here are some recent highlights from the InVEST program:

Launched in FY24

SNOOPI

The Signals of Opportunity P-band Investigation (SNOOPI), a 6-unit CubeSat, demonstrated the feasibility of root zone soil moisture and snow water equivalent measurements without a transmitter, by reusing existing signals from telecommunications satellites. SNOOPI reduced the risk of this technique for future 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. SNOOPI launched March 2024.

HyTI

Also launched in March 2024, the Hyperspectral Thermal Imager (HyTI) 6-unit CubeSat aimed to demonstrate high-spatial, spectral, and temporal resolution thermal infrared (TIR) imagery acquisition from low Earth orbit. Although the mission was cut short by the effects of a 2024 solar storm, an updated version of the HyTI instrument will be included on the ACMES payload (see opposite page).

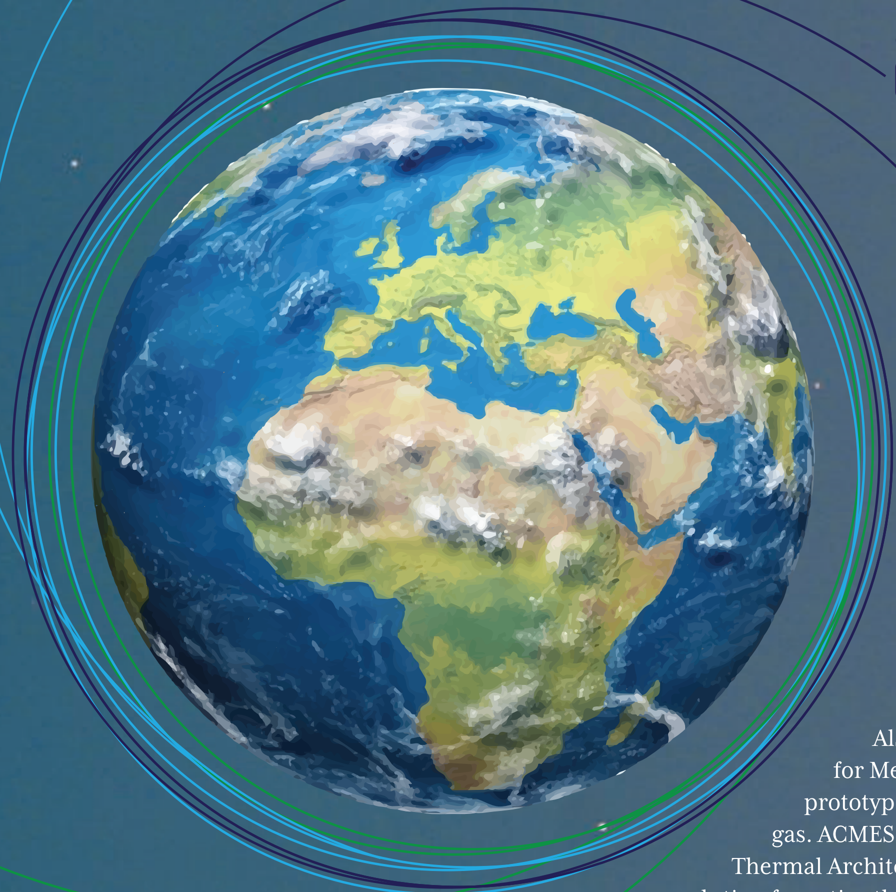
Launching in FY25

ARGOS

The Aerosol Radiometer for Global Observation of the Stratosphere (ARGOS) is a hosted payload instrument that will test a new technique for observing atmospheric aerosols. Leveraging eight distinct limb views, the compact instrument will be useful for understanding how wildfires, volcanoes, and severe weather events might affect aerosols.

ARCSTONE

ARCSTONE will test a new on-orbit calibration technique using the Moon as a reference to ensure space-based Earth science instruments remain accurate over time. From a 6-unit CubeSat, the hyperspectral instrument will provide lunar spectral reflectance measurements needed to establish an absolute lunar calibration standard for past, current, and future Earth observing sensors.



Launching in FY26

GRITTS

The Geodetic Reference Instrument Transponder for Small Satellites (GRITTS) will verify a new geodetic measurement concept on a 16-unit CubeSat. Functioning as a compact GNSS L-to-X-band transponder, GRITTS could pave the way for a more cost-effective mission, employing a constellation of spacecraft for better global coverage and improved accuracy.

ACMES

Also a 16-unit CubeSat, the Active Cooling for Methane Sensor (ACMES) instrument will prototype a novel system for observing methane gas. ACMES will advance two technologies: first, Active Thermal Architectures (ATA), a complete end-to-end solution for active thermal control of cryogenic instruments on nano and small satellites; second, the Filter Incidence Narrow-band Infrared Spectrometer (FINIS), a sensor designed for space-based detection of methane sources.

Timeline of ESTO Launches

2013: COVE, IPEX
2014: GRIFEX
2015:
2016: RAVAN, IceCube
2017: MIRATA, RainCube, TEMPEST-D
2018: CubeRRT, CSIM-FD, HARP
2019: CIRiS
2020
2021: NACHOS 1&2
2022: CTIM, MURI
2023: HyTI, SNOOPI
2024: ARGOS, ARCSTONE
2025
Beyond: ACMES, GRITTS, GloTEMP, GRATTIS & ODIN

STUDENT SPOTLIGHT

Students are integral to the work and success of technology development teams. Since ESTO's founding, at least 1,320 students from 181 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 FY24 alone, at least 253 students from 69 institutions were involved with active technology development projects.

Anthony Ge

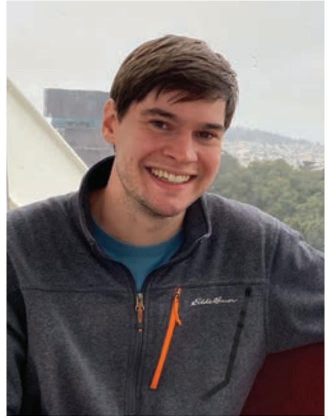
Anthony Ge is a junior at the University of Pennsylvania, where he studies Digital Media Design. His interest in data visualization, real-time rendering, and applications of game development for science purposes were immensely useful to Thomas Grubb's AIST project for visualizing data from NASA's GEOS instrument. Anthony built on work accomplished in 2023 by fellow student Jackie Li, creating a 3D data visualization tool that allows users to dynamically load, animate, and transform GEOS data sets within a virtual reality environment. As he heads into senior year, Anthony would like to continue exploring real-time rendering and graphics programming. When Anthony isn't creating dynamic data visualizations for Earth science applications, he enjoys practicing guitar drawing, and playing soccer.

Anusha Srirenganathan

Anusha Srirenganathan is a fourth-year PhD candidate at George Mason University. She specializes in using artificial intelligence and machine learning to study air quality. As part of Chaowei Yang's AIST effort to create a digital twin for monitoring air quality, Anusha fused MODIS, GOES-R, MERRA2, and in-situ data to obtain a continuous, high-resolution survey of air quality data nationwide. After completing her PhD, Anusha plans to continue her research, developing techniques for incorporating new data sets from sources like MAIA and TEMPO into air quality models. In her free time, she enjoys spending time with her dog and painting.

Kaia Wolfe

Kaia Wolfe is a junior at the University of California, Davis, where she studies mechanical engineering. Her specialty is computational engineering, with a focus on simulation software and CAD modeling. Supporting Sarath Gunapala's IIP project dedicated to creating a compact infrared imager, Kaia created a detailed SCAD model of the proposed c-FIRST instrument, as well as physical models for realistic visualization and showcasing. As she heads into senior year, Kaia is considering a double major in aerospace engineering and preparing to take the Fundamentals of Engineering exam. When she isn't preparing to become a professional engineer, Kaia enjoys traveling, hiking, and trying new foods.



Bryan Shaddy

Bryan Shaddy is a fourth-year PhD candidate studying mechanical engineering at the University of Southern California. His research focuses on methods for data assimilation based on deep learning, with applications in wildfire modeling. In support of Kyle Hilburn's FireTech project, Bryan developed a data assimilation technique that uses conditional generative algorithms to predict wildfire progression during early stages of a fire based on satellite measurements. After finishing his PhD, Bryan plans to continue working with deep learning approaches for data assimilation and modeling in Earth science, either in industry or government.

Mariah Schwartz

Mariah Schwartz just earned her PhD in Electrical Engineering at Ohio State University, with research focused on the fabrication and characterization of novel architectures for avalanche photodiodes, which has immediate applications for Earth observation – especially greenhouse gases. She used that expertise to support Sanjay Krishna's ACT project, investigating planar and double-mesa device architectures that could reduce the size, weight, and power of future instruments. After completing her PhD, Mariah began working for Northrop Grumman's Advance Technology Laboratory. In her free time, she enjoys exercising and cooking.

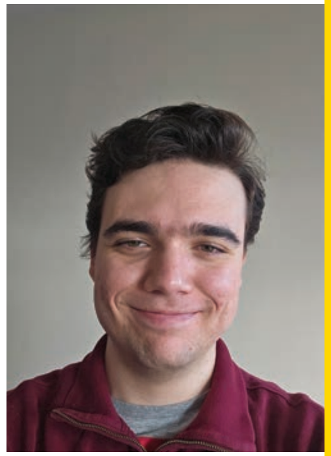
Hossein Rajoli

Hossein Rajoli is a second-year PhD candidate at Clemson University. His research interests focus on artificial intelligence, especially multi-modal learning related to wildfire detection and management. Supporting Fatemeh Afghah's FireTech effort to organize drone swarms capable of observing wildfires, Hossein developed a model that leverages RGB and IR modalities to detect obscured fires and hotspots hidden beneath thick smoke and forest canopies. In his free time, he enjoys hiking and spending time with his family and friends.

Vrushabh Zinage

Vrushabh Zinage is a fifth-year PhD candidate at the University of Texas, Austin, where he develops practical algorithms for autonomous systems. Supporting Srinivas Bettadpur's IIP project to develop quantum sensors for measuring Earth's gravitational field, Vrushabh integrated machine learning with established control systems to improve attitude control for geodetic instruments. This novel approach significantly reduced attitude error in real-time and could make future space missions dedicated to measuring Earth's gravity more efficient without major modifications to existing control architectures. After finishing his PhD, Vrushabh plans to continue im proving space-based remote sensors at JPL. In his free time, Vrushabh enjoys star gazing, watching cricket, and listening to music.

Adam Bahlous-Boldi



Adam Bahlous-Boldi is a second-year graduate student at MIT, where he studies small-satellite instrumentation, optics, and space systems. As a member of John Leckey's SPECIES team, which aims to create a compact LiDAR system for small satellites, Adam created a computational optical model that will assess the performance of the instrument's deployable diffractive optical element. After completing his PhD, Adam wants to work in a cutting-edge research position at NASA or lead his own lab as a professor. In his free time, Adam enjoys hiking in the New Hampshire White Mountains, composing music on the piano, and playing chess.

Abbigail Breitfeld

Abbigail Breitfeld is a fifth-year PhD candidate at Carnegie Mellon University, where she specializes in mobile robot trajectory planning for science missions. She leveraged that expertise to support Steve Chien's AIST project, which aims to enable novel, autonomous sensors for Earth observation. Specifically, Abbigail tested a collection of machine learning algorithms that could help autonomous sensors interact with clouds more effectively. After completing her PhD in December of 2025, Abbigail plans to continue working on navigation and trajectory planning for spacecraft at JPL. In her free time, she enjoys hiking, kayaking, and ultimate frisbee.

STUDENT SPOTLIGHT

Ananya Rao

Ananya Rao is a fourth-year PhD Candidate at Carnegie Mellon University. Her research focuses on path-planning and coordination for multi-agent systems and autonomous exploration. As part of her PhD research, she supported Steve Chien's AIST project, developing scoring functions that assess how well different satellites in a multi-satellite constellation could fulfill observation requests. This work later became a decentralized scheduling algorithm that enables fluid sensor webs to assemble and disband according to new observational needs. As she finishes her PhD, Ananya looks forward to a career in academia, where she hopes to train the next generation of robotics researchers and continue collaborating with NASA. In her free time, Ananya enjoys hiking, creative writing, and exploring cafes and bookstores.

Akseli Kangaslahti

Akseli Kangaslahti is a senior at the University of Michigan, Ann Arbor, where he studies computer science, artificial intelligence, and automated decision making. As an intern at NASA's Jet Propulsion Laboratory (JPL), Akseli contributed to Steve Chien's AIST project, implementing a sensor web that achieved high-resolution monitoring of flood events at a global scale. He's also contributed constraints and utility models for simulation studies, as well as improved search algorithms for planning satellite observations. Once he's completed his bachelor's degree, Akseli plans to begin his PhD. When he's not supporting NASA technology projects, Akseli enjoys skiing, ice hockey, soccer, and golf.

Arnold Kellen

Arnold Kellen is a fifth-year PhD candidate at Vanderbilt University. His research focuses include nanoscale design and radiation hardness for photonic integrated circuits in space instruments. Arnold supported Mark Stephen's ACT project based at NASA's Goddard Space Flight Center, contributing to the simulation and design of an on-chip serial arrayed waveguide grating, as well as device and system characterization efforts. After Arnold completes his PhD, he plans to leverage his skills to develop next generation PIC systems for applications like space instrumentation, communication systems, and quantum computing. In his free time, Arnold enjoys hiking, cycling, photography, and live music.

Jonathon Hirschi

Jonathon Hirschi is a fourth-year PhD candidate at the University of Colorado, Denver. His research focuses on machine learning applications for Earth science, especially the relationship between physical problems and modern artificial intelligence techniques. Supporting Kyle Hilburn's FireTech project for observing wildfires more effectively, Jonathon is working on a method for minimizing errors in AI models describing very dry fuels, which have a greater potential for wildfire spread. Jonathon is currently working on his dissertation, which will focus on a variety of neural networks designed to process time sequence data. In his free time, Jonathon enjoys hiking, cycling, fishing, and pampering his two small dogs.

NASA MSI Incubator: Wildfire Climate Tech Challenge

In March, ESTO hosted the Wildfire Climate Tech Challenge, awarding three teams $100,000 for their diverse, innovative approaches to address the escalating effects of wildfires and climate change. The challenge combined the expertise of Minority Serving Institutions – including Historically Black Colleges and Universities, Tribal Colleges and Universities, Hispanic-serving institutions, and others – with NASA resources to enhance Earth science and technological capabilities to support operational fire management agencies. The winners were "Team Howard U," from Howard University; "Team Flare," from University of San Francisco; and "Team Horizon Force" from North Carolina A&T State University.

For more information about this challenge, visit:

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