National Aeronautics and Space Administration

EARTH SCIENCE TECHNOLOGY OFFICE

2023 Annual Report
25th Anniversary

Executive Summary

Earth's climate is changing, increasing the likelihood of costly impacts to society from weather and flooding events, extreme temperatures, and the proliferation of wildfires. For decades, NASA has collected data from the vantage point of space to understand climate changes resulting from human and natural effects. But we don't just study the climate, we act on it. 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. I'm very proud of the accomplishments of ESTO-funded projects during 2023, with numerous technology advances for Earth science as well as the competitive selection of new projects.

In March 2023, ESTO celebrated its 25th birthday, a significant milestone for our organization and one that served as a catalyst for us to look back at 25 years of noteworthy successes. With over 1,100 technology developments funded since our inception in 1998, ESTO has an abundance of projects that highlight our organization's unique role within NASA's Earth Science Division. We chose 25 such stories to highlight, which the reader can explore further in the section "ESTO Impacts: A 25th Anniversary Project" on page 14.

In fiscal year 2023 (FY23), ESTO continued to build upon this 25-year heritage of technology development. This year, 31% of active ESTO technology projects advanced at least one Technology Readiness Level (TRL), and at least 18 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 157 students – high school through PhD – were directly involved in ESTO-funded projects this year.

The year also began with the departure of ESTO Director Pamela Millar, who helmed our organization for six years. The ESTO team is profoundly grateful for her leadership and her more than 30 years of NASA service. In September 2023, I was selected as the new director for ESTO, and I am deeply honored by this selection. I take the challenge of this position seriously and recognize the high visibility of our work and the critical role our office serves. Under my leadership, ESTO will remain a successful, respected organization that is operating under a proven business model. We have a truly outstanding community, from our program managers and staff to our principal investigators and their teams, and I am excited to continue ESTO's legacy of enabling Earth science through the development of groundbreaking technologies.

Michael Seablom
Program Director

SpaceX's Transporter 6 launches MURI alongside 113 other satellites from Kennedy Space Center on January 3, 2023. MURI will help researchers learn more about everything from wildfires to marine ecosystems. Credit: SpaceX

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 arelies 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

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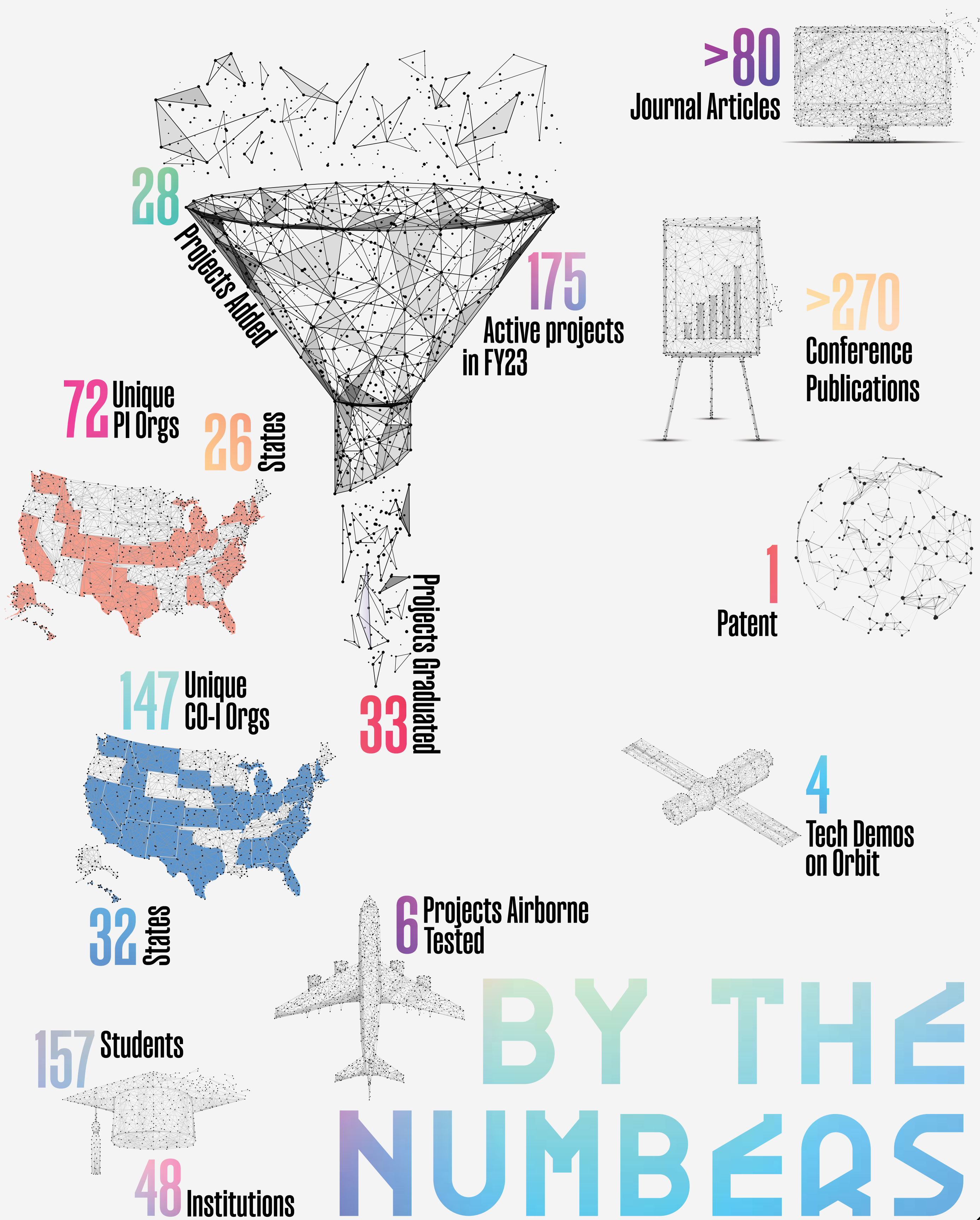


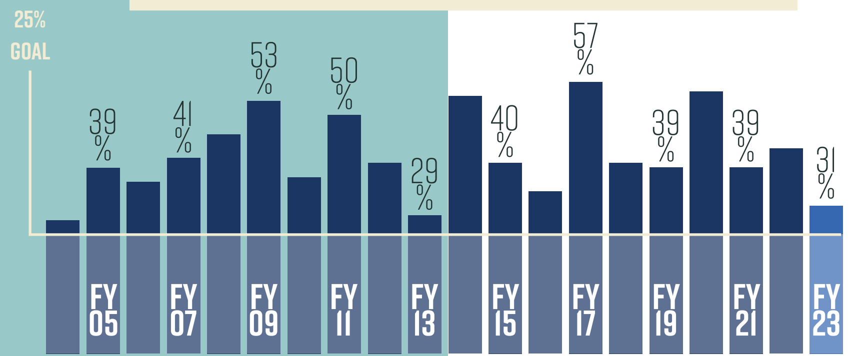
FY23 METRICS

With over 1,100 technology investments made since 1999 and an active portfolio of 175 projects during FY23 (October 1, 2022, through September 30, 2023), ESTO drives innovation, enables future Earth science observations, and strengthens NASA's reputation for developing and advancing leading-edge technologies. To highlight the FY23 achievements, what follows are the year's results tied to ESTO's performance metrics.

GOAL 1: TECH READINESS

FY23 RESULT

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



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

31% of ESTO technology projects funded during FY23 advanced at least one TRL over the course of the fiscal year, and at least 10 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%.

GOAL 2: INFUSION

FY23 RESULT

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

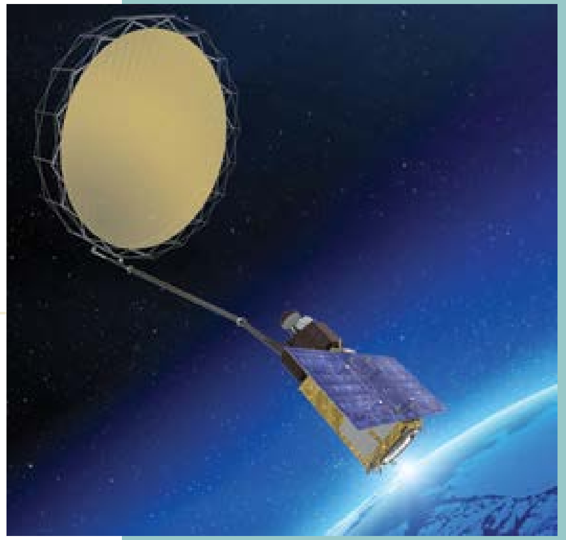
In this fiscal year, at least 18 ESTO projects achieved infusion into science measurements, airborne campaigns, data systems, or follow-on development activities. Three notable examples follow.

INFUSION HIGHLIGHT: SUPPORTING EPCAPE

Equipment lines the Ellen Browning Scripps Memorial Pier for the Eastern Pacific Cloud Aerosol Precipitation Experiment project. Credit: K.C. Alfred / The San Diego Union-Tribune

In Spring 2023, two new atmospheric radar instruments developed through ESTO, CloudCube and the Vapor In-Cloud Profile Radar (VIPR), were deployed to the Scripps Pier in La Jolla, CA, to support the Department of Energy's Eastern Pacific Cloud Aerosol Precipitation Experiment (EPCAPE). A year-long, campaign, EPCAPE seeks to characterize the cloud cover, cloud thickness, cloud altitude, radiative properties, aerosol interactions, and precipitation of stratocumulus clouds in the eastern Pacific. VIPR, a 2016 Instrument Incubator Program (IIP) investment, is obtaining humidity profiling inside of clouds as well as precipitation with high vertical resolution. CloudCube, a 2019 IIP award, is measuring the vertical profile of clouds and precipitation as well as Doppler velocities.

INFUSION HIGHLIGHT: DETECTING RFI FOR ESA

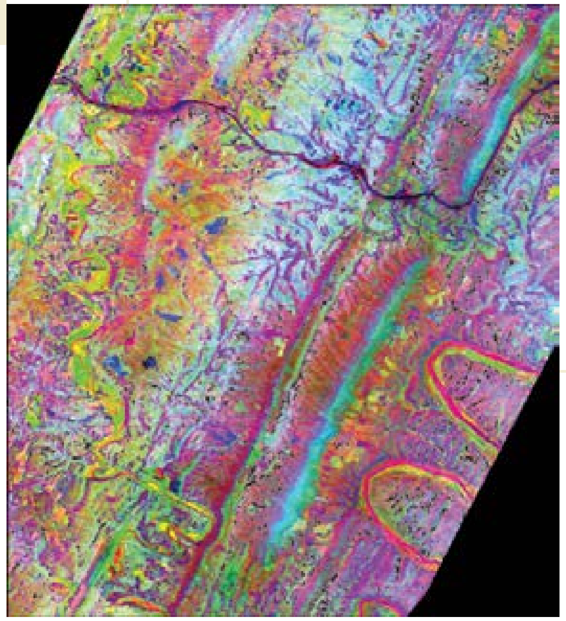


An artist's depiction of ESA's CIMR mission Credit: Thales Alenia Space

The real-time RFI processing demonstrated by ESTO's CubeSat Radiometer Radio Frequency Interference Technology (CubeRRT) validation project is being applied to two European Space Agency (ESA) missions: The Copernicus Imaging Microwave Radiometer (CIMR) mission will carry a wide-swath conically-scanning multi-frequency microwave radiometer to provide observations of sea-surface temperature, sea-ice concentration, and sea-surface salinity, and the Meteorological Operational (MetOp) series of satellites provide weather data services.

INFUSION HIGHLIGHT: NEW TOOLS FOR ORNL DAAC

A spectral image of forested land in western Maryland taken by the Airborne Visible/Infrared Imaging Spectrometer - Classic (AVIRIS-C) instrument. Credit: NASA



The Ecological Spectral Information System (EcoSIS), a set of open-source software tools and data-derived spectral models developed under the Advanced Information Systems Technology (AIST) program, is being transitioned to operational use at the Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC). ORNL DAAC, one of several NASA data archives, specializes in terrestrial biogeochemistry, ecology, and environmental processes.

FY 23 PROGRAM UPDATES

GOAL 3: SCIENCE MEASUREMENT PROJECT HIGHLIGHT: MURI INSTRUMENT SEES FIRST LIGHT

>> Enable a new science measurement or significantly improve the performance of an existing technique. Several projects satisfied this goal in FY23. One notable example follows:

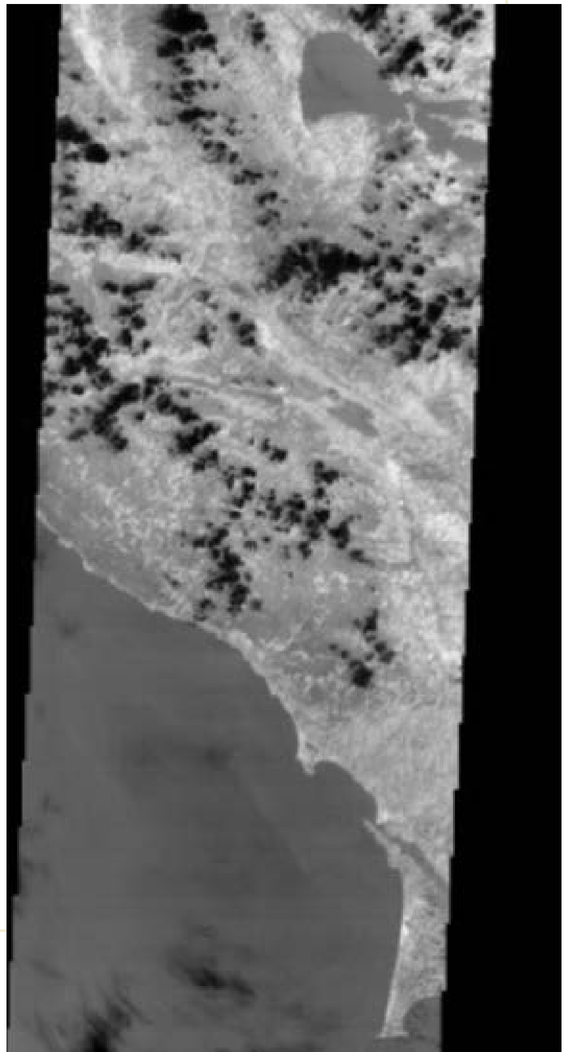
Developed at Leonardo DRS with support from ESTO, the Multiband Uncooled Radiometer Imager (MURI) instrument has taken several months of imagery from orbit. MURI is demonstrating its ability to take accurate, highly-sensitive measurements of Earth's surface temperature, as high as 123 milli-kelvin, comparable to the existing Landsat Thermal InfraRed Sensor (TIRS) instruments.

The MURI project is testing a new two-band longwave infrared (10.8um and 12.0um) radiometric imager that utilizes an uncooled focal plane array. Thermal infrared data describing Earth's surface temperature is critical for learning more about a host of complex Earth systems, from wildfires to marine ecosystems.

Traditional space-based thermal sensors typically require bulky, heavy cryogenic coolers – the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the Aqua and Terra satellites weighs more than 500 pounds. By contrast, MURI weighs only about 12 pounds. While MURI's microbolometer still needs to be held at a constant temperature to maintain accuracy in space, that temperature can be ambient "room temperature."

MURI is also a high-resolution thermal imager. Earlier instruments like the Compact Infrared Radiometer in Space (CIRiS) CubeSat had a ground sample distance of more than 250 meters, while MURI is capable of better than 90 meters, and the ground sample distance of Landsat TIRS is >100 meters.

MURI was launched by the SpaceX Transporter 6 on January 3, 2023, as one of several hosted payloads within the Loft Orbital YAM5 SmallSat.



A portion of Northern California, featuring Clear Lake in the top right, as seen by MURI on May 9, 2023. Credit: NASA / Leonardo DRS

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.

6 PROJECTS ACTIVE IN FY23

DSI PROJECT HIGHLIGHT: DEPLOYABLE METALENSES

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: JPL

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. 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.

55 PROJECTS ACTIVE IN FY23

14 PROJECTS GRADUATED

Onboard Processing and Retasking Flight Experiment Onboard Spaceborne Computing 2 (SBC-2) Payload on the International Space Station (ISS) – Steve Chien, NASA JPL

Creation of a Wildland Fire Analysis: Products to enable Earth Science – Janice Coen, NCAR

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

Preparing NASA for Future Snow Missions: Incorporation of the Spatially Explicit SnowModel in LIS – Ethan Gutmann, NCAR

Surrogate modeling for atmospheric chemistry and data assimilation – Daven Henze, University of Colorado Boulder

Air Quality Analytics Collaborative Framework (ACF) – Thomas Huang, NASA JPL

New Observing Strategy - Live Demonstration of Vegetation Disturbance Virtual Field Campaign – Sujay Kumar, NASA GSFC

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

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

Ground Stations as a Service (GSaS) for Near Real-time Direct Broadcast Earth Science Satellite Data – Louis Nguyen, NASA LaRC

Quantum Computing for Earth Science and Classical Machine Learning for Image-to-Image Translation of Earth Images – Eleanor Rieffel, NASA ARC

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

Improving ground-level air quality prediction by integrating spatiotemporal new observation system datasets and numerical simulations – Chaowei (Phil) Yang, George Mason University

Mining Chained Modules in Analytic Center Framework – Jia Zhang, Southern Methodist University

6 PROJECTS ADDED

Dynamic Targeting – Steve Chien, NASA JPL

Transition of CAPRi (Cloud-based Analytical framework for Precipitation Research) to NASA Earth Information System (EIS) – Sujay Kumar, NASA GSFC

Assessing Neighborhood Climate Risk and Daily Exposures in Cities – Alex Ruane, GISS

Development of Digital Twin Technologies for Climate Projections – Gavin Schmidt, GISS

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

Blockchain Distributed Ledger for Space Resource Access Control – Yelena Yesha, University of Miami

AIST PROJECT HIGHLIGHT: NEW SOFTWARE FOR FUTURE HALE SYSTEMS

NASA's "Centurion" HALE aircraft. ILEOS will help future HALE systems observe everything from volcanic eruptions to greenhouse gases. Credit: NASA

A new NASA navigation software will help high-altitude aircraft observe Earth systems autonomously, paving the way for novel science missions dedicated to observing everything from atmospheric chemistry to climate change.

Developed by a team of researchers at NASA, the United States Geological Survey (USGS), and the Johns Hopkins University Applied Physics Laboratory, the Intelligent Long Endurance Observing System (ILEOS), will calculate custom flight paths for High Altitude, Long Endurance (HALE) systems – unmanned aircraft that observe Earth from the stratosphere.

HALE systems will one day fly for months at a time, and maximizing the value of those airborne science missions requires complex calculations that take into account not only the desired data, but also constraints like sensor type, aircraft variety, and flight conditions.

"We are developing the planning capability," said Meghan Chandarana, a Computer Engineer at NASA's Ames Research center and principal investigator for the project.

"ILEOS is basically leveraging all of the science domain knowledge that we currently have from satellites, aircraft, and whatever other sources to decide where to send these high-altitude vehicles to take the best measurements, for whatever data a scientist might want to take," Chandarana explained.

ILEOS will lay the foundation for HALE systems to have dynamic targeting capabilities, ensuring instruments fixed to drones, airships, balloons, and other aircraft don't miss interesting features that may suddenly appear during their flight, such as severe weather events.

Chandarana explains that her team's ILEOS software architecture includes three key components: a target generation pipeline, a science observation planner, and an intuitive user interface.

The target generation pipeline and observation planner plot targeted observables for HALE systems to study during their flight, while the user interface allows researchers to provide requirements and manage HALE missions. The system will also establish a footing from which future scientists may coordinate fleets of HALE systems dedicated to the same science mission.

Custom data processing algorithms are the backbone of ILEOS. The core algorithms are well established, but Chandarana and her team will tailor them to fit the unique constraints of HALE-based instruments.

"We're not inventing a new algorithm, those algorithms exist. It is the inferences we make to give it the constraints, and how we put those algorithms together to create this whole pipeline of planning, essentially, that is novel," said Chandarana.

By the end of her project, Chandarana and her team aim to demonstrate the scientific utility of ILEOS with simulations featuring a variety of HALE systems and instruments. One of those simulations, Chandarana said, may feature CHAPS-D, another ESTO-funded technology dedicated to observing air pollution and greenhouse gases.

"CHAPS-D is one of the up-and-coming sensor payloads that could be utilized for gathering this kind of data that a scientist would want, essentially, so you can think of it as one sensor payload that could be used on a HALE vehicle that ILEOS will then plan the mission for," she said.

Chandarana emphasizes the value of having a large, diverse team of subject matter experts collaborating on ILEOS together. Coordinating across agencies, specialties, and time zones is no easy feat, but Chandarana and her team did so with distinction.

"It's not every day that we get a team that has scientists and technologists in the same place. The thought is to integrate both from the beginning, so you're intentional with the way you're developing your software," said Chandarana.

ADVANCED COMPONENT TECHNOLOGY

Component and sub-system technologies are a principle 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.

37 PROJECTS ACTIVE IN FY23

15 PROJECTS ADDED

Earth-observing PIC (EPIC) Component Development – Mate Adamkovics, Lockheed Martin

GHG PIC Spectrometer – Mate Adamkovics, Lockheed Martin

Design for Atomic Gravity Gradiometer for Earth Research (DAGGER) – Matthew Cashen, Vector Atomic Inc

Ultra RF – William Deal, Northrop Grumman Corporation

Metasurface Antenna for Cloud-Targeting Radar (MACTRad): W-Band Metasurface Cloud Sensor – Aaron Diebold, MetaCept Inc

Compact ultra-violet spectropolarimetry enabled by meta-grating technologies – Brian Drouin, NASA JPL

Develop and Demonstrate a Broadband Detector (0.20 to 50 micron) for Measuring Earth's Radiation Budget – Achyut Dutta, Banpil Photonics Inc

Low-power Integrated Acousto-Optics for Atomic Quantum Sensors – Peter Rakich, Yale University

Heterogeneous Integration of High Operating Temperature Barrier IR Detectors and Waveguides: Integrated Photonics for IR Hyperspectral Sensing – Stephanie Sandor-Leahy, Northrop Grumman

Solid Underconstrained Multi-Frequency Deployable Antenna – Jonathan Sauder, NASA JPL

Metalens Origami Deployable Lidar (MODeL) Telescope – Mark Stephen, NASA GSFC

Low Cost, Size, Weight, and Power, Radiation Hard, Time-of-Flight LiDAR or Infrared Radiometry System on a Chip for Earth Orbit and Planetary Missions – Ramy Tantawy, SenseICs Corporation

Quantum Atomic Rydberg Radiometer for Earth Measurements (QuARREM) – Shane Verploegh, ColdQuanta

Low SWaP-C Modular Laser Architecture for Laser-Cooled Quantum Sensors and Atomic Clocks – Kurt Vogel, Vescent Photonics Inc

Ultra-compact Machine-Learning-driven platform for room temperature mid-wave infrared remote sensing – Daniel Wasserman, University of Texas at Austin

6 PROJECTS GRADUATED

Geodetic Reference Instrument Transponder for Small Satellites (GRITSS) – Christopher Beaudoin, University of Massachusetts Lowell

Planar Metasurface Reconfigurable W-band Antenna for Beam Steering – Nacer Chahat, NASA JPL

Visible to SWIR Fast eAPDs for Panchromatic FTS Instrument – Arvind D'Souza, Leonardo DRS

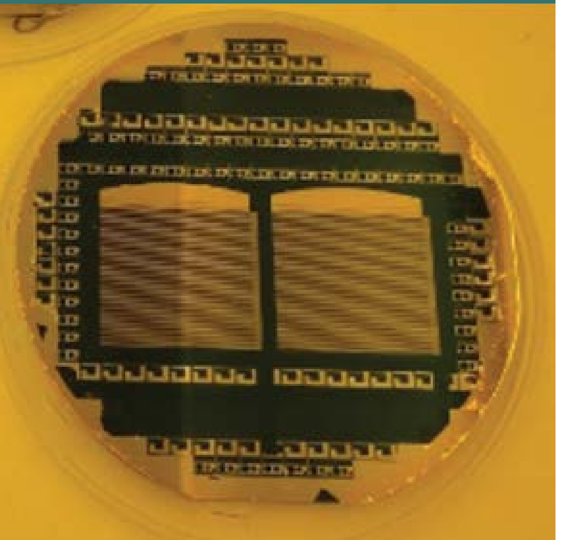
Laser transmitter for space-based water vapor lidar – Tso Yee Fan, MIT Lincoln Lab

Very Long Wavelength Infrared Focal Plane Arrays for Earth Science Applications – Sarath Gunapala, NASA JPL

IMPRESS Lidar: Integrated Micro-Photonics for Remote Earth Science Sensing Lidar – Jonathan Klamkin, University of California Santa Barbara

ACT PROJECT HIGHLIGHT: METASURFACE ANTENNA

This 5cm×5cm metasurface antenna on a gallium arsenide substrate was developed by a recently-graduated ACT project (PI: Nacer Chahat, JPL). The W-band antenna offers the electronic beam-steering performance of a typical phased array, with much lower power consumption, making it compatible with CubeSats. Image credit: JPL



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.

46 PROJECTS ACTIVE IN FY23

8 PROJECTS GRADUATED

A Solar Occultation Instrument Suitable for Constellations of Small Satellites – Scott Bailey, Virginia Tech

Frequency Comb Spectrometer for Satellite Atmospheric Remote Sensing – Kevin Cossel, NIST

GNSS Reflections Multistatic Radar for Wetland Dynamics – Jeff Dickson, NASA JPL

Compact Total and Spectral Solar Irradiance Sensor (CTSIS) Mission Concept Study – David Harber, University of Colorado Boulder

Stratospheric Water Inventory, Tomography of Convective Hydration (SWITCH) – Nathaniel Livesey, NASA JPL

Aerosol Wind Profiler – John Marketon, NASA LaRC

CARBO: The Carbon Balance Observatory – Charles Miller, NASA JPL

Miniaturized Lidar Sensor for Fire and PBL Payloads – Edward Nowottnick, NASA GSFC

1 PROJECTS ADDED

Quantum Gravity Gradiometer (QGG) Tech Demo – Norman Lay, NASA JPL

IIP PROJECT HIGHLIGHT: SENSING SNOW

From February through April 2023, a new, extremely-compact radar system for snow water equivalent (SWE) measurements was tested on a series of drone flights near the Mores Creek Summit Snotel sensor in Idaho. The radar – a 2016 IIP project called the Enhanced MeTaSurface (EMTS), PI: Hans-Peter Marshall, Boise State University – operates in the Ku-Band and C-Band and leverages complementary metal oxide semiconductor (CMOS) system-on-chip electronics with a compact metasurface antenna to provide an instrument package weighing less than 2 kg and consuming less than 10 W of power.

Credit: Hans-Peter Marshall / Boise State

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 FY23

2 PROJECTS GRADUATED

HyperAngular Rainbow Polarimeter HARP CubeSat – Jose Vanderlei Martins, University of Maryland Baltimore County

Compact Infrared Radiometer in Space (CIRiS) – David Osterman, Ball Aerospace

INVEST PROJECT HIGHLIGHT: FIRST LIGHT DATA OUTSHINES EXPECTATIONS

First-light data from NASA's Compact Total Irradiance Monitor (CTIM) became publicly available this year, paving the way for new insights into Earth's relationship with total solar irradiance.

Dave Harber, Principal Investigator for CTIM and Instrument Engineer at the University of Colorado's Laboratory for Atmospheric and Space Physics (LASP), presented this data at the American Meteorological Society's 2023 Annual Meeting.

Harber has also published a collection of CTIM first-light data to their website, lasp.colorado.edu/ctim/data.

"Perhaps the most surprising result so far is the stability of the detectors. We have not observed any statistically significant degradation of the primary detectors yet over 250 hours of direct unfiltered solar exposure," said Harber.

CTIM's first-light data includes solar and deep-space measurements collected during twelve orbits. It's is a promising start for a technology validation mission that could help researchers better understand severe weather, climate change, and other global forces.

CTIM, which launched July 2022, is the smallest instrument ever dispatched to study total solar irradiance and will help scientists determine if small satellites could be as effective at measuring total solar irradiance as larger instruments like the Total Irradiance Monitor (TIM).

"Although the first light dataset was relatively short, we've used subsequent on-orbit measurements taken over the following four months to refine temperature corrections and the deep-space model used to analyze those measurements," said Harber.

CTIM features a unique, ultra-black bolometer made of vertically aligned carbon nanotubes, which Harber and his team developed alongside colleagues from the National Institute of Standards and Technology. Though Harber expected the material to perform well, he was surprised by just how effective CTIM's detectors proved to be even in the rigors of space.

"From lab testing we did expect the vertically aligned carbon nanotube optical absorber to be quite stable, but the on-orbit performance to this point has exceeded our expectations," said Harber.

CTIM's mission is expected to last until mid-2024.

Credit: Virgin Orbit

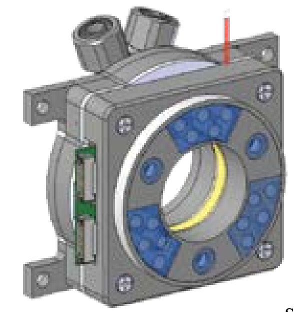
SUSTAINABLE LAND IMAGING TECHNOLOGY

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.

8 PROJECTS ACTIVE IN FY23

SLI-T PROJECT HIGHLIGHT: IMPROVED LANDSAT CALIBRATION

The Improved Radiometric calibration of Imaging Systems (IRIS) is a full-spectrum, end-to-end onboard calibration source approximately 90% smaller than existing calibration sources. The instrument component builds on successes pioneered by ATLIS-P, another SLI-T project, to demonstrate a functionally complete prototype land imager, one that maintains absolute radiometric calibration for the full duration of a spaceflight mission – an essential technology development for creating the next generation of cost-efficient, compact satellites.



Credit: Raytheon

FIRESENSE TECHNOLOGY

FireSense Technology seeks new, innovative Earth system observation capabilities to predict and manage wildfires and their impacts. This program is partnering with NASA's Earth Action and Research and Analysis elements, the Aeronautics Research Mission Directorate, the Space Technology Mission Directorate, 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 5-6 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.

7 PROJECTS ADDED

AI-enabled Drone Swarms for Fire Detection, Mapping, and Modeling – Fatemeh Afghah, Clemson University

Technology Development to Integrate Innovative Observation Capabilities into Coupled Wildfire Models for Improved Active Fire Forecasting – Kyle Hilburn, Colorado State University

Wildfire Thermal Detection Instrument Development – Simon Hook, NASA JPL

The airborne Compact Fire Imager (CFI) for measurements across the entire fire lifecycle – Douglas Morton, NASA GSFC

8 PROJECTS ACTIVE IN FY23

Distributed Spacecraft with Heuristic Intelligence to monitor Wildfire Spread for Responsive Control – Sreeja Roy-Singh, Bay Area Environmental Research Institute

UAS thermal infrared spectroscopy will improve real time evaluation of hazards and environmental impacts of wildfires – James Thompson, University of Texas at Austin

Pyro-atmosphere Infrared Sounder: Monitoring Fire Weather Conditions with a Sub-Kilometer Spatial-Resolution Hyperspectral Infrared Sounder – Sun Wong, NASA JPL

YEARS

ESTO Impacts: A 25th Anniversary Project

Over the last 25 years, the Earth Science Technology Office (ESTO) has managed the development of more than 1,100 new technologies for future science measurements. This diverse, forward-looking portfolio has nurtured new Earth-observing capabilities, informed Decadal Surveys and strategic planning, and generated numerous infusions and spinoffs.

At least 269 ESTO technologies have been infused into Earth science missions, science campaigns, or other operational or commercial activities over the last two and a half decades.

While every ESTO project has a story to tell – indeed, an impasse often informs progress more than a runaway success – this highlight series focuses on some of the most notable impacts. Please join us in celebrating these achievements as well as the broad successes of the Earth science technology program.

WINDEX: The Dawn of GPS Reflectance for Ocean Surface Wind Measurements

Early testing of WINDEX utilized several airborne platforms, including a first-generation AAI Aerosonde UAV. Credit: AAI Corporation

In the mid-1990s, a presidential executive order made available the full precision of the Global Positioning System, or GPS, to the public. An explosion of applications followed, from car GPS to cell phone maps to shipping container tracking devices. At the time, Stephen Katzberg of at the NASA Langley Research Center (LaRC) wondered about the reflection of L-band GPS signals off the surface of the ocean: "What's the effect of water roughness?" and "Can you relate signal disturbance to the wind that creates that roughness?"

As it turned out, you can. Water is like a polished mirror for GPS, and wind acting on a body of water increases the roughness in the water's surface, causing detectable changes in the signal reflection.

With funding from ESTO and LaRC, Katzberg developed and tested the Wind Explorer (WINDEX) airborne instrument, which successfully detected the variances of the reflected signal and, using a processing algorithm, correlated those properties to determine surface wind speed.

With a low mass/volume/power instrument package, WINDEX could be flown on almost any platform, and it saw initial test flights on both NASA's Boeing 757 and the diminutive AAI Aerosonde UAV (3.5 m wingspan). In the early 2000's, the instrument was installed on the NOAA P-3 Hurricane Hunter 'Miss Piggy' and proved its value for near-continuous surface wind measurements alongside buoys and dropsondes data.

WINDEX-derived GPS instruments are today ubiquitous tools for storm tracking, weather forecasting, and the characterization of ocean wind fields, and they can still be found onboard the NOAA Hurricane Hunters.

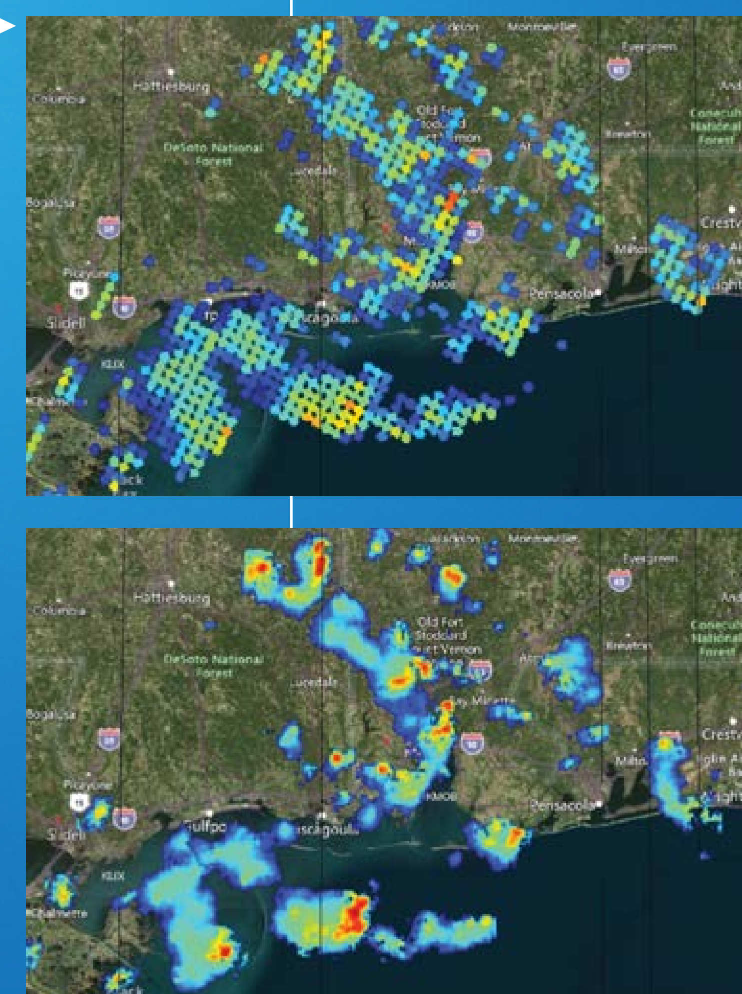
WINDEX also led to the development of the NASA Cyclone Global Navigation Satellite System (CYGNSS) – eight micro-satellite observatories launched in 2016 that make frequent measurements of ocean surface winds throughout the life cycle of tropical storms.

CAPRi: An Advanced Analytic Framework for Processing GPM Precipitation Data

As many as 40,000 thunderstorms can occur around the world every day, according to NOAA. Forecasting these storms and other precipitation events globally is one of the most challenging – and most important – missions in NASA's Earth Observatory portfolio.

In 2018, a group of ESTO-funded researchers developed the Cloud-based Analytical framework for Precipitation Research (CAPRi), a tool for processing data from the Global Precipitation Measurement (GPM) mission more efficiently, ultimately reducing the amount of time it takes for researchers to validate GPM data by a factor of 48.

GPM is an ongoing international space mission led by NASA and the Japanese space agency, JAXA, to provide researchers with real-time descriptions of precipitation events at a global scale. Using data from the GPM Validation network, which uses ground-based radar to validate space-based precipitation measurements, CAPRi successfully trained a collection of machine learning algorithms to validate precipitation data automatically.



Standard GPM data (top) and high-resolution GPM data produced by CAPRi (bottom). CAPRi increased the speed at which researchers can produce high-resolution precipitation data by a factor of 48. Credit: GPM / NASA

In addition to reducing the amount of time it takes for researchers to validate data, CAPRi also increased the spatial resolution of space-based precipitation measurements – an important goal highlighted in the 2010 Decadal Survey.

Whereas previous data processing systems could only achieve about five kilometers per pixel, CAPRi achieved resolutions as fine as approximately one kilometer per pixel.

VISAGE, another ESTO-funded project, paved the way for CAPRi's success. VISAGE helped researchers use machine learning to process precipitation data gathered during airborne field campaigns, and that work influenced CAPRi's own collection of convolutional neural networks.

Today, CAPRi continues helping the GPM team validate precipitation data gathered by space-based sensors, but it could someday contribute to other NASA science missions. The same CAPRi analytic framework that trained machine learning algorithms to process precipitation data more efficiently could also train machine learning algorithms to process a wide variety of Earth science data sets.

HARP Instrument Proved New Approach for Atmospheric Aerosol Measurements

Vanderlei Martins, Roberto Borda, and Dominik Cieslak with a full-size model of HARP at UMBC. Credit: Marlayna Demond, UMBC

Before deorbiting in April 2022, the Hyper-Angular Rainbow Polarimeter (HARP) CubeSat spent 777 days in low Earth orbit validating a novel, compact imaging polarimeter designed to observe atmospheric aerosols.

The HARP polarimeter observed how light scatters off of aerosols – airborne particles that have an impact on many variables, from air pollution to climate change – to determine their size, shape, and chemical composition. Before HARP, researchers were unsure whether small satellites were capable of hosting such an instrument.

Led by Jose Vanderlei Martins, Director of the Earth and Space Institute at the University of Maryland, Baltimore County (UMBC), a team of scientists developed a polarimeter that splits three identical images into independent detector arrays using a unique prism. This allowed HARP to achieve highly-accurate, simultaneous imagery of three polarization states with minimal hardware.

In 2020, the 3-unit CubeSat won the 2020 "Small Satellite Mission of the Year" award from the American Institute of Aeronautics and Astronautics. HARP also has the distinction of being the 100th CubeSat mission supported by NASA's CubeSat Launch initiative.

Other NASA missions have already used – or plan to use – identical HARP instruments to monitor aerosol-cloud interactions from aircraft and space-based platforms.

Two airborne campaigns – NASA's Aerosol Characterization from Polarimeter and Lidar (ACEPOL) and the Lake Michigan Ozone Study (LMOS) – relied heavily on technology innovations first pioneered by HARP. Both campaigns used an airborne version of the space instrument known as AirHARP to observe aerosol particles and clouds.

Vanderlei and his team are also developing HARP-2 for NASA's Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission, which will help us better understand how the ocean and the atmosphere exchange carbon dioxide. HARP-2's role will be to reveal how aerosols might fuel phytoplankton growth in the uppermost area of the ocean surface.

OceanWorks: Speeding Up Ocean Science

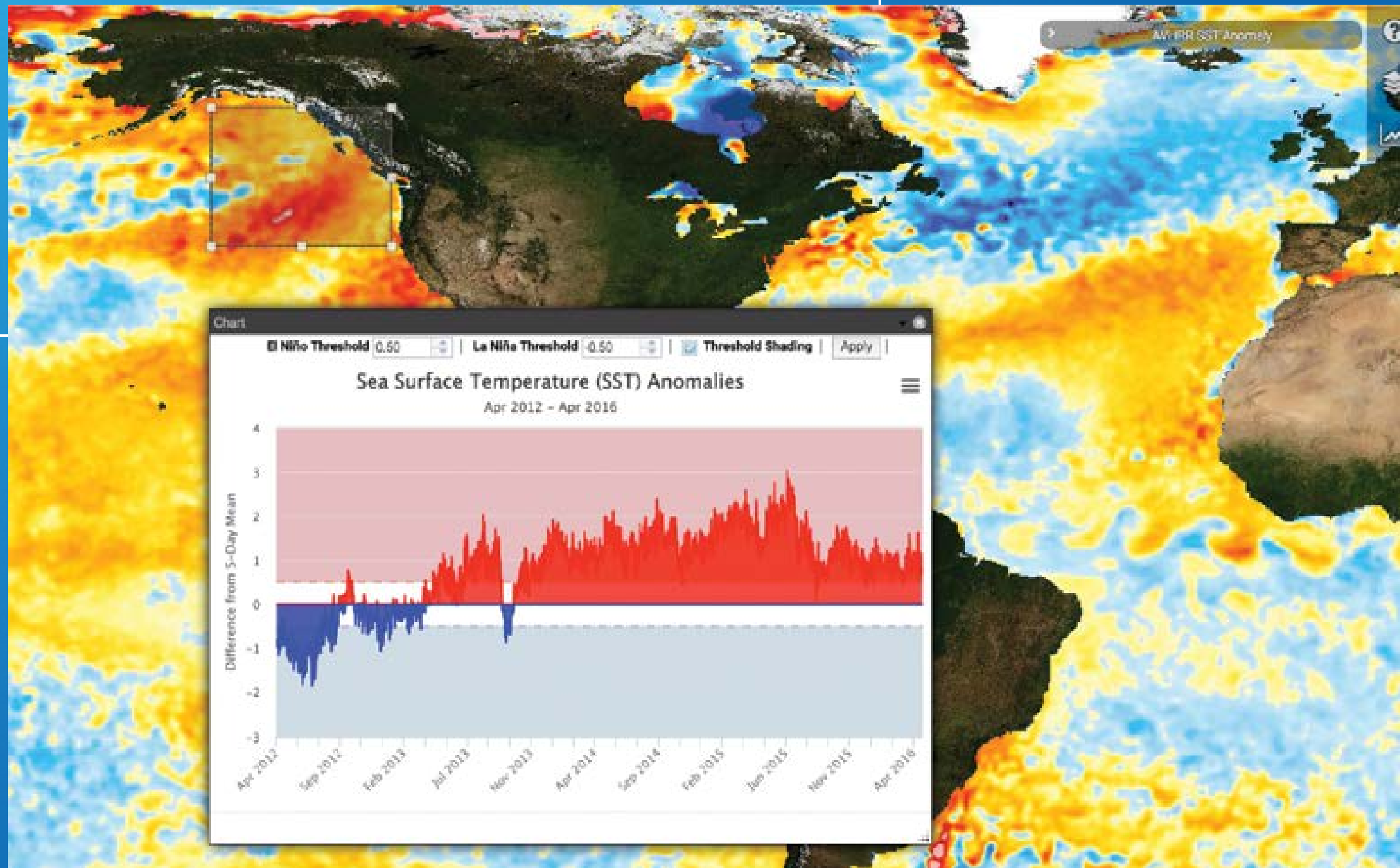
As the Surface Water and Ocean Topography (SWOT) mission progressed to eventual launch in 2022, researchers realized that manual data manipulation approaches would be infeasible with greatly expanded data volumes. At the time it was estimated that SWOT could generate over 20 Petabytes during a nominal three-year mission.

OceanWorks, an open-source, big-data platform developed under the Advanced Information System Technologies (AIST) program was infused into NASA's Physical Oceanography Distributed Active Archive Center (PO.DAAC) in 2019, ahead of the SWOT mission. The science platform streamlined many data gathering and analysis functions; in some cases, tasks that previously took weeks-to-months to accomplish were reduced to less than an hour.

A collaborative effort between the Jet Propulsion Laboratory, Florida State University, NCAR, and George Mason University, OceanWorks provided a new environment for conducting ocean science investigations, including on-the-fly multi-variable analysis for major ocean parameters. And as a web-accessible service, OceanWorks enabled direct analysis of the PO.DAAC archive, including subsets, without having to move the data.

OceanWorks was built upon three prior AIST investments, all awarded in 2014:

- OceanXtremes: Oceanographic Data-Intensive Anomaly Detection and Analysis Portal (Thomas Huang, Jet Propulsion Laboratory)
- DOMS: Distributed Oceanographic Matchup Service (Shawn Smith, Florida State University)
- MUDROD: Mining and Utilizing Dataset Relevancy from Oceanographic Data (Chaowei Yang, George Mason University)



An early example of OceanWorks' web-based analysis capability (from the OceanXtremes project), this image shows "The Blob" – the large mass of relatively warm water in the Pacific Ocean off the coast of North America from 2013-2015. Credit: Thomas Huang, JPL

Early Laser Research Spins Off to Support Medical Applications

In 2005, a Thulium (Tm) fiber laser developed by IPG Photonics with NASA funding was demonstrated as an emerging tool for urologic procedures by Dr. Nathaniel Fried at the Johns Hopkins School of Medicine and Keith Murray of NASA Langley Research Center. Originally developed for wind measurements with funding from ESTO's Laser Risk Reduction Program (LRRP), the fiber laser has since been commercialized by at least six vendors for use in minimally invasive procedures, particularly for treatment of kidney stones.

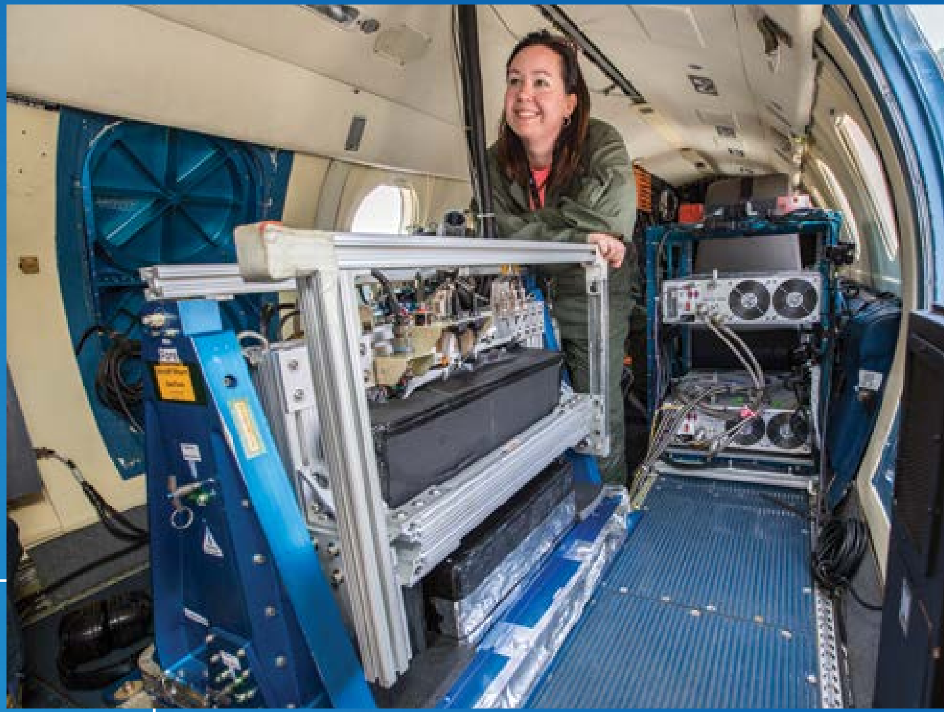
Fried, who is now at the University of North Carolina at Charlotte, has authored several dozen journal articles about medical applications for the Tm laser. He recalled that "the Tm fiber was a promising new technology that had several advantages over Holmium:YAG lasers – the gold-standard for several decades."

Holmium:YAG laser systems, which today can be found in nearly every hospital setting, are used during lithotripsy to break up kidney stones to be more easily flushed out of the body. A Tm fiber laser works essentially the same way. However, Fried said, "a Tm laser originates in fiber itself, which produces a more uniform, more precise beam and uses smaller optical fiber compared to Holmium:YAG, which means there's more room for flushing out stone fragments through the ureteroscope." The Tm fiber laser also has a much higher wall-plug efficiency – roughly 12% vs 1-2% for Holmium:YAG – and is much smaller and quieter.
Fried estimated that perhaps 10%, and growing rapidly, of the approximately 300,000 laser lithotripsies performed in the U.S. each year use a Tm fiber system. He also noted there are emerging applications for dermatology and other medical disciplines as well.

For Earth science, lasers and lidar remote sensing enable measurements of variables such as sea elevation, atmospheric composition, wind profiles, cloud cover, ice mass, and vegetation canopy. The LRRP was established in 2001 to formalize the design, testing, and development of durable laser systems, particularly in the critical 1- and 2-micron wavelengths, and many LRRP projects found their way into follow-on instrument development. The LRRP ended in 2010.

Histological image from initial testing in 2005, showing the laser's impact on a tissue sample. The Tm fiber laser leaves a clean, distinct cut, or kerf, with little damage to the surrounding tissue. Credit: N. Fried

GeoTASO Instrument Paves the Way for the TEMPO Mission



GeoTASO (foreground) being prepared for a LISTOS science flight on NASA's HU-25 aircraft. Credit: NASA/David C. Bowman

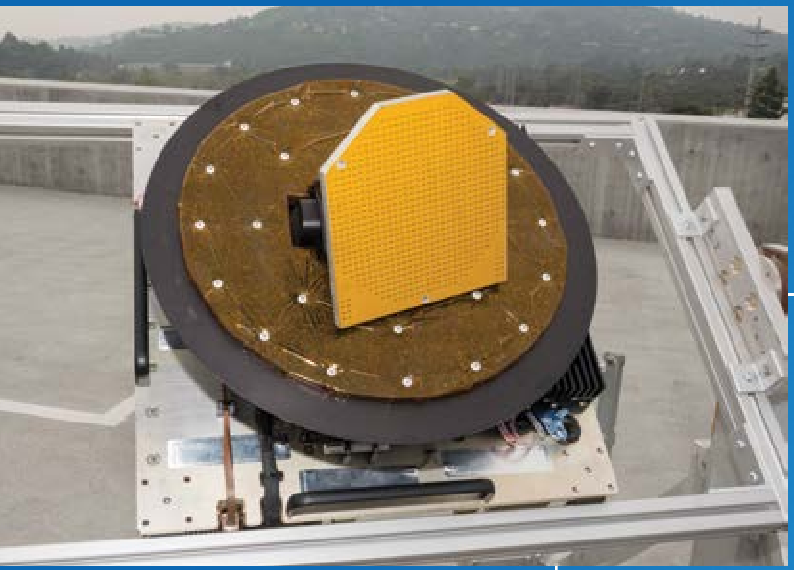
The Geostationary Trace gas and Aerosol Sensor Optimization (GeoTASO) instrument, developed through a 2010 Instrument Incubator Program award by Principal Investigator James Leitch at Ball Aerospace, is an airborne, nadir-viewing, UV-Visible spectrometer that measures aerosols and trace gases like ozone and formaldehyde.

Originally conceived as a precursor for the air quality measurements called for by the Geostationary Coastal and Air Pollution Events (GEO-CAPE) decadal survey mission concept, GeoTASO has become an airborne science instrument as well as a test bed for the Tropospheric Emissions: Monitoring of Pollution (TEMPO) mission.

TEMPO launched in April 2023 and includes a UV-Visible sensor, also built by Ball Aerospace, which will provide hyperspectral data very similar to that of GeoTASO.

In 2013, GeoTASO teamed up with several other instruments for a multi-year airborne science campaign called DISCOVER-AQ. Onboard the NASA HU-25C Falcon, GeoTASO flew higher and faster than the other instruments, which offered satellite-analog measurements to advance the TEMPO mission concept and refine its trace gas and aerosol retrieval approaches.

GeoTASO also contributed some 50 flight hours to the Long Island Sound Tropospheric Ozone Study (LISTOS), a 2018 field campaign led by a consortium of state air-quality agencies in the Northeastern U.S.



The DopplerScatt radar at JPL, before being attached to the bottom of a King Air B200 plane. Credit: NASA/JPL-Caltech

Realizing Simultaneous Ocean Wind and Current Measurements

In 2016, an airborne instrument developed at the Jet Propulsion Lab called DopplerScatt conducted several validation flights onboard a Department of Energy B200 aircraft. The Ka-band Doppler scatterometer demonstrated its ability to take simultaneous measurements of ocean surface vector winds and currents – a new science capability that has helped improve our understanding of air-sea interactions and their influence on Earth's climate.

While prior instruments measured ocean currents or wind individually, DopplerScatt could do both, providing a new perspective on sea surface properties and air-sea interactions.

DopplerScatt utilizes a spinning transmitter that bounces radar off the ocean's surface to take measurements in multiple directions at once. It calculates the Doppler effect of the return signal to determine speed and trajectory. Those measurements are combined with data from a scatterometer, which calculates wind speed and direction from the "scattering" of the radar signal by the roughness of the ocean surface.

By 2017, DopplerScatt was used on two airborne science campaigns alongside other instruments.

The Submesoscale Processes and Lagrangian Analysis on the Shelf (SPLASH) campaign led by the Consortium for Advanced Research on Transport of Hydrocarbon in the Environment (CARTHE), used DopplerScatt to investigate the movement of potential oil spills and leaks in the Gulf of Mexico.

DopplerScatt also participated in the Keck Institute for Space Studies Controlled, Agile, and Novel Ocean Network (CANON) campaign. It provided an overhead view of currents while autonomous, robotic vehicles and gliders gathered in situ data at various depths in Monterey Bay.

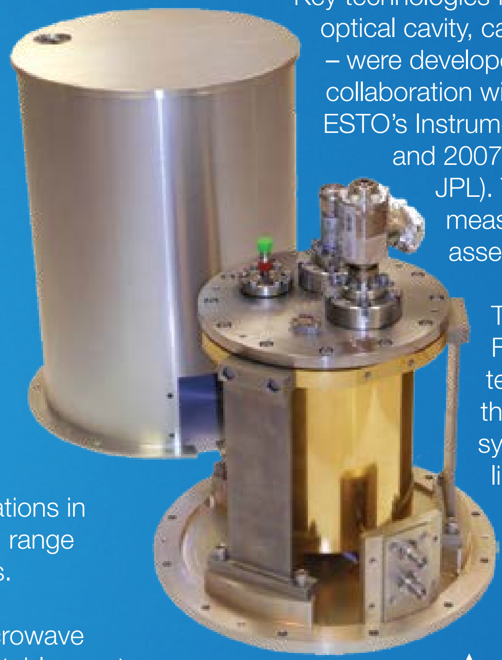
To date, DopplerScatt has logged over 350 flight hours on NASA aircraft, taking measurements and participating in science campaigns such as the Sub-Mesoscale Ocean Dynamics and Vertical Transport Experiment (S-MODE). While DopplerScatt will continue to be used on future NASA airborne science missions, the technology also lays the groundwork for an eventual spaceborne instrument, which would enable global measurements of ocean surface winds and water currents simultaneously for the first time.

A Laser Focus for Gravity Measurements

The twin satellites of the Gravity Recovery and Climate Experiment Follow-On (GRACE-FO), developed in partnership with the German Research Center for Geosciences and launched in 2018, provide a dramatic view of Earth's variable gravity and mass distribution and spurred new insights in a variety of scientific fields. Like its predecessor, GRACE (launched in 2002), GRACE-FO is producing discoveries with far-reaching impacts on society, from hydrology and geophysics to ice mass estimates and global sea levels.

The measurement technique pioneered by GRACE, and utilized by GRACE-FO, works by detecting the slight changes in the movement of the twin satellites relative to each other as they orbit Earth. Subtle variations in gravity can be detected using careful range measurements between the satellites.

Like GRACE, GRACE-FO uses a microwave ranging instrument, referenced to a stable quartz clock and coupled with precise GPS tracking, to measure these minute changes to within a few microns. GRACE-FO also demonstrated an advanced laser instrument that has shown significant improvements in the accuracy of inter-spacecraft ranging. The laser system owes its advantages largely to the shorter wavelength of the laser, compared to the microwave wavelength, as well as a thermally isolated optical cavity, which is more stable than the quartz clock.



Key technologies for the laser demonstration – the optical cavity, cavity assembly, and ranging electronics – were developed at the Jet Propulsion Lab in collaboration with Ball Aerospace with funding from ESTO's Instrument Incubator Program funding in 2002 and 2007 (Principal Investigator: William Folkner, JPL). The German Space Program provided measurement optics and the steering mirror assembly along with instrument integration.

To date, the laser system on GRACE-FO has operated flawlessly as a technology demonstration alongside the primary microwave interferometry system and is widely regarded as the likely primary instrument for the next gravity mission. Data from the laser demonstration are available at the Physical Oceanography Distributed Active Archive Center (PO.DAAC).

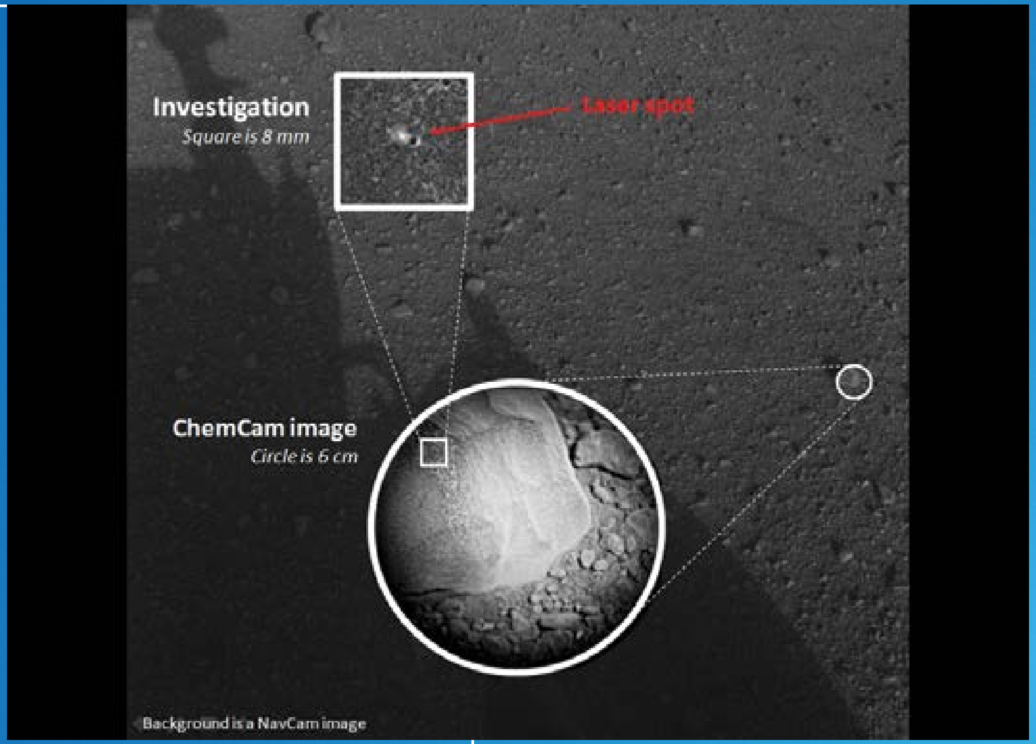
Prototype assembly and thermal enclosure (approximately 10" tall) for the advanced laser cavity. The cavity itself is made using glass with a low coefficient of thermal expansion to maintain a constant distance between end mirrors. Credit: W. Folkner

An artist's depiction of the GRACE-FO laser demonstration. Credit: NASA

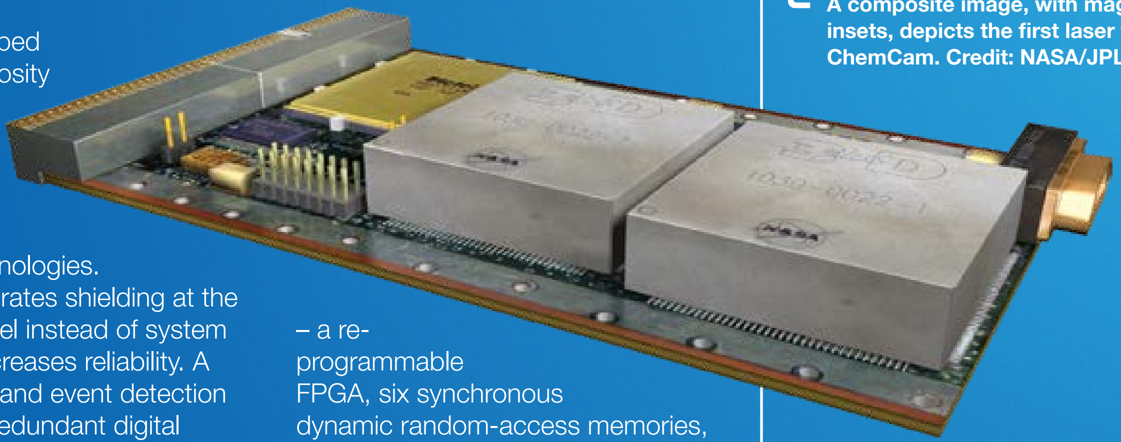
Radiation Tolerant Memory for Curiosity Observations

In 2009, a memory array developed at the Langley Research Center was selected for use on the Chemistry & Camera (ChemCam) instrument onboard the Mars Science Laboratory (MSL) Curiosity rover. The Radiation Tolerant Intelligent Memory Stack (RTIMS), originally developed for Earth-observing missions at geostationary and low Earth orbit, features state-of-the-art chip stacking construction, radiation shielding, and radiation mitigation technologies.

On Mars, RTIMS has controlled the firing of the Curiosity's ChemCam laser, data acquisition, data buffering, and communication with the Rover Compute Element. ChemCam uses a laser to vaporize materials up to nine meters away on the surface and analyze the elemental composition of those materials.



A composite image, with magnified insets, depicts the first laser test by ChemCam. Credit: NASA/JPL

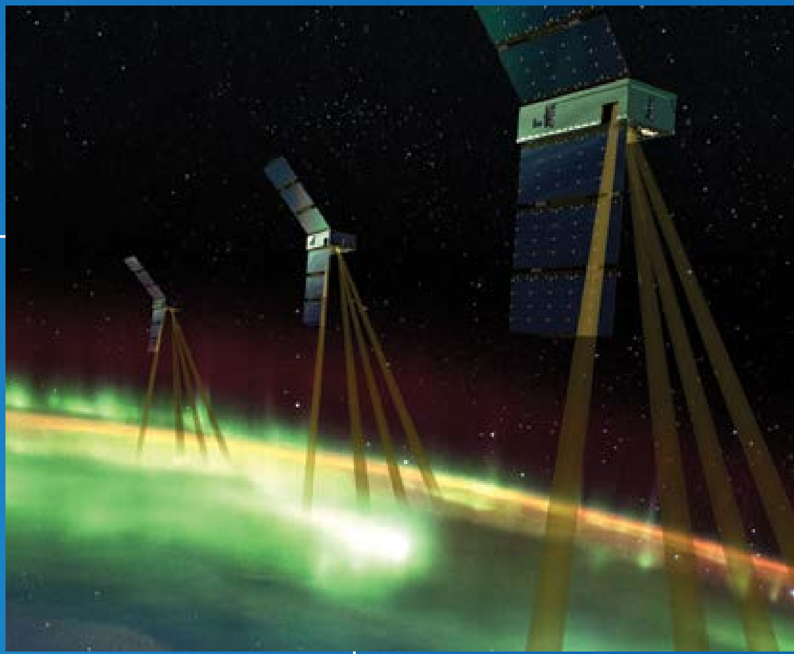


RTIMS has helped safeguard Curiosity observations with novel radiation shielding and radiation mitigation technologies. RTIMS incorporates shielding at the component level instead of system level, which increases reliability. A self-scrubbing and event detection system, triple redundant digital memory, and in-flight-reconfigurability further improve radiation tolerance, allowing RTIMS to overcome errors and adapt to changing mission conditions.

RTIMS also provides a significantly smaller and lighter memory array: At 42.7mm x 42.7mm x 13.0mm, RTIMS reduced the footprint by nearly 80%. By stacking individual chips, heterogeneous electronic parts – a re-programmable FPGA, six synchronous dynamic random-access memories, a linear regulator, and the radiation mitigation circuitries – could be built into a single component.

MSL was not the only ride into space for RTIMS. Astrium, a European aerospace company, used RTIMS arrays for communications satellites, and 3D Plus Inc., a partner in the development of RTIMS, has also commercialized and sold the modules for a variety of applications.

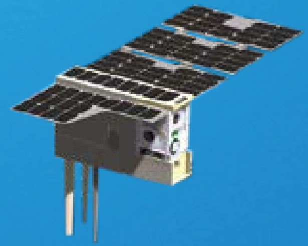
Significant Technology Heritage in EZIE Heliophysics Mission



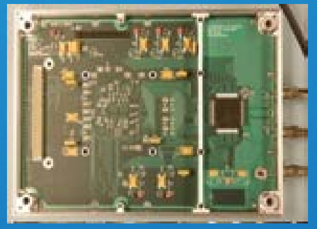
An artist's depiction of the EZIE mission. Credit: Johns Hopkins University Applied Physics Laboratory

The Electrojet Zeeman Imaging Explorer (EZIE) mission, selected in 2020 by NASA's Heliophysics Science Division and set to launch in 2024, will explore the 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 the 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 (ADD) 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. The ADD has enjoyed widespread infusion and formed the basis for RFI detection on the Soil Moisture Active Passive (SMAP) mission. The ADD was also used on the Hurricane Imaging Radiometer (HIRAD), an airborne instrument that measures rain rate and ocean surface wind speed.

SpaceCube: Meeting On-Board Processing Requirements for Future Science Missions

SpaceCube team members are pictured here with some of the family of SpaceCube products. From left to right: Alessandro Geist; Dave Petrick; Tom Flatley; and Gary Crum. The products include (from left to right): SpaceCube 1.0 and 1.5 prototypes; SpaceCube 2.0 and Mini prototypes; and SpaceCube 1.5 flight unit. Credit: Bill Hrybyk/NASA

For nearly two decades, the SpaceCube program at Goddard Space Flight Center (GSFC) has provided a series of processors that have been infused into multiple missions and applications. With funding from several ESTO awards starting as early as 2008, GSFC Internal Research and Development (IRAD) support, and other external partnerships, these reconfigurable spaceflight data processing systems provide 10x to 100x improvements in computing power while lowering power consumption and cost.

The SpaceCube team realized early on that the sophistication of space-based science instruments was quickly outpacing the capabilities of existing space-qualified data processing systems. While radiation-hardened and proven, the available systems could not provide the speed or power needed to handle vast amounts of data. And sensor autonomy, artificial intelligence, and deep learning were beginning to add brand new computing demands.

Their approach abandoned the traditional path of developing bespoke radiation-hardened flight processors that were consistently a generation or two behind commercial processors. Instead, they used the latest “radiation-tolerant” processing elements coupled with integrated upset detection and correction architecture to provide both reliability and computing power.

The SpaceCube series of on-board processors – from the original SpaceCube 1.0 through SpaceCube 3.0 and SpaceCube Mini-Z+, along with a full range of SpaceCube Cards for specific applications – have seen enormous success and have generated at least seven patents.

SpaceCube processors have enabled more than 20 missions, including NASA’s Robotic Refueling Mission-3, Restore-L Robotic Servicing Mission, and Asteroid Redirect Robotic Mission. The U.S. Department of Defense (DoD) has also adopted the technology.

Most recently, in March 2023, the SpaceCube Edge Node Intelligent Collaboration (SCENIC) experiment was launched to the International Space Station (ISS) on board the DoD Space Test Program-Houston 9 (STP-H9) mission. One of eight experimental payloads on STP-H9, SCENIC is a testbed to evaluate artificial intelligence and machine learning on FPGAs and custom microchips. On ISS, SCENIC will demonstrate autonomy, decision-making, and sensor collaboration; assess performance and radiation-tolerance; and offer an ongoing testing platform for uploading new algorithms and capabilities.

Building the Land Information System

In the early 2000s, new Earth-observing satellites like Terra, Aqua, and Aura gave researchers access to terabytes of novel data, enabling them to study some of Earth’s most complicated systems in unprecedented detail.

But transforming those vast troves of information into accessible data products remained a significant challenge. ESTO’s Computational Technologies (CT) and Advanced Information Systems Technology (AIST) programs helped a team of researchers from NASA’s Goddard Space Flight Center solve that problem.

Led by Christa Peters-Lidard, the team developed the Land Information System (LIS), a software framework that turns satellite and ground-based observational data into high-resolution models of terrestrial water and energy cycles.

Using machine learning and a highly modular system design, LIS can consume large amounts of raw data and produce predictive models with unprecedented accuracy.

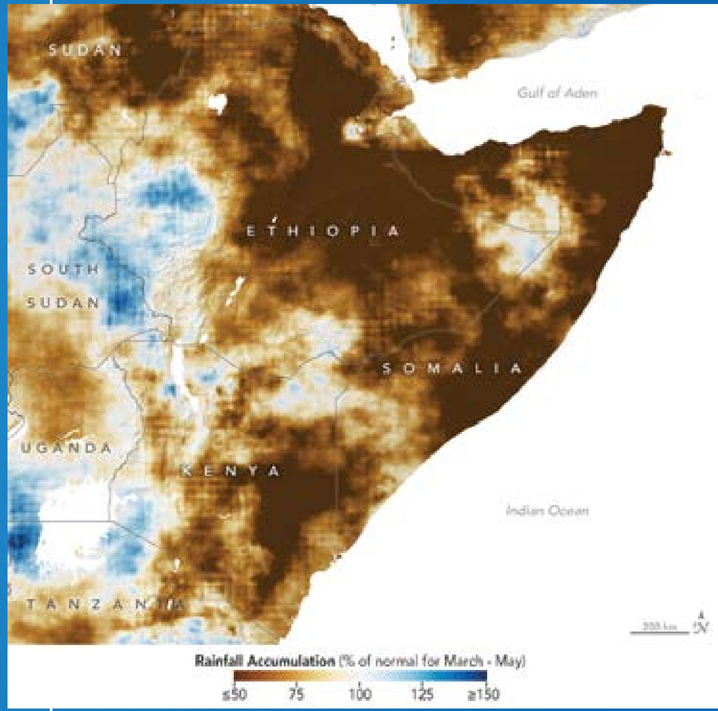
Today, researchers apply LIS models managed by NASA to handle a wide variety of applications, from helping the United States Agency for International Development predict famines to supporting the United States Air Force with detailed weather forecasts.

LIS was one of ESTO’s earliest projects. Co-recipient of the NASA’s 2005 “Software of the Year” award, it quickly became an essential tool not only for NASA researchers, but for Earth scientists around the world.

Subsequent AIST funding helped Peters-Lidard, who currently serves as the Director of NASA’s Sciences and Exploration Directorate, and her team take LIS even further.

A 2005 AIST grant awarded to Sujay Kumar, now a NASA Research Physical Scientist, integrate LIS into a broader sensor web. A 2008 AIST grant created a new, general optimization subsystem for the software framework, while a 2011 AIST grant led to a mission simulation and evaluation platform.

LIS will continue to play a critical role in NASA’s efforts to better understand complex Earth systems. The software will soon help researchers produce a new operational hydrology environment for flood forecasting and process high-resolution data from TEMPO, the latest addition to NASA’s Earth Observing System.



A NASA model describing rainfall in East Africa. With NASA’s Land Information System, researchers can produce detailed models describing complex Earth systems. Credit: NASA

Early Technology Developments for the TROPICS Mission

In May 2023, the TROPICS (Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats) mission successfully launched its first 3-unit CubeSats, part of a constellation to study the development of tropical cyclones. Arrayed in three orbital planes, the TROPICS satellites will use scanning microwave radiometers to measure temperature, humidity, precipitation, and cloud properties.

The TROPICS mission was made possible by significant ESTO-funded technology developments as well as precursor on-orbit demonstrations. A 2010 Advanced Component Technology (ACT) project at MIT Lincoln Laboratory developed and demonstrated a new hyperspectral microwave receiver subsystem to support atmospheric sounding missions like TROPICS. A key technology in that effort was an ultra-compact, nine-channel intermediate frequency processor (IFP) module. Weighing about 500 grams and requiring less than 100 cubic centimeters, the IFP enabled much smaller instruments – at the time more than 10-times smaller – and opened opportunities for lowered launch costs and new observation scenarios.

Each of the CubeSats in the TROPICS constellation contains a high-performance radiometer based on this early technology work. Working together, the CubeSats comprise an observing system that offers an unprecedented combination of horizontal and temporal resolution for the measurement of tropical cyclones at a nearly global scale. The TROPICS mission is also helping to demonstrate that constellations can provide an affordable, reconfigurable solution for Earth remote sensing.

The ACT microwave receiver technology has also been infused into several other projects, including the ESTO-funded Microwave Radiometer Technology Acceleration (MiRaTA) CubeSat, launched in November 2017, and the NOAA-funded Microsized Microwave Atmospheric Satellite Version 2a (MicroMAS-2a) CubeSat, launched in January 2018. Although the MiRaTA CubeSat bus experienced radio failure early in its mission, both demonstrations helped inform the design and development of TROPICS.

A mixed-signal printed circuit board for the intermediate frequency processor module developed as part of the ACT project. Credit: W. Blackwell, MIT

DAWN: A Robust Airborne Wind Lidar

Developed at NASA Langley Research Center under principal investigator Michael Kavaya, the Doppler Aerosol WiNd (DAWN) instrument is a Doppler wind lidar that provides high-resolution 3D wind measurements. Originally intended as a step toward an eventual spaceborne lidar system, the 2-micron, pulsed, coherent-detection wind profiling system has proven significant utility as an airborne instrument, with numerous flights in support of atmospheric science field campaigns.

A benchtop version of DAWN was first funded in 2004 under the Instrument Incubator Program (IIP), building upon prior work on 2-micron laser development through the Laser Risk Reduction Program (LRRP). A follow-on award through the IIP 2007 solicitation allowed the project team to further package and ruggedize the system for its first test flights.

At the time, DAWN laser pulse energy was the highest to date in an eye-safe wind lidar system – 10 pulses per second at 100 mJ, with 200 ns pulse duration – and provided previously unattainable 3D wind profiles every 3-7 km with a vertical resolution of ~50 m as well as 12 line-of-sight azimuth angles that could be processed into accurate horizontal wind vectors and wind variation information.

Beginning in 2010, DAWN was deployed on NASA's DC-8 aircraft, alongside several other instruments, in support of the NASA Genesis and Rapid Intensification Processes (GRIP) flight campaign, a multi-year effort to study hurricane development.

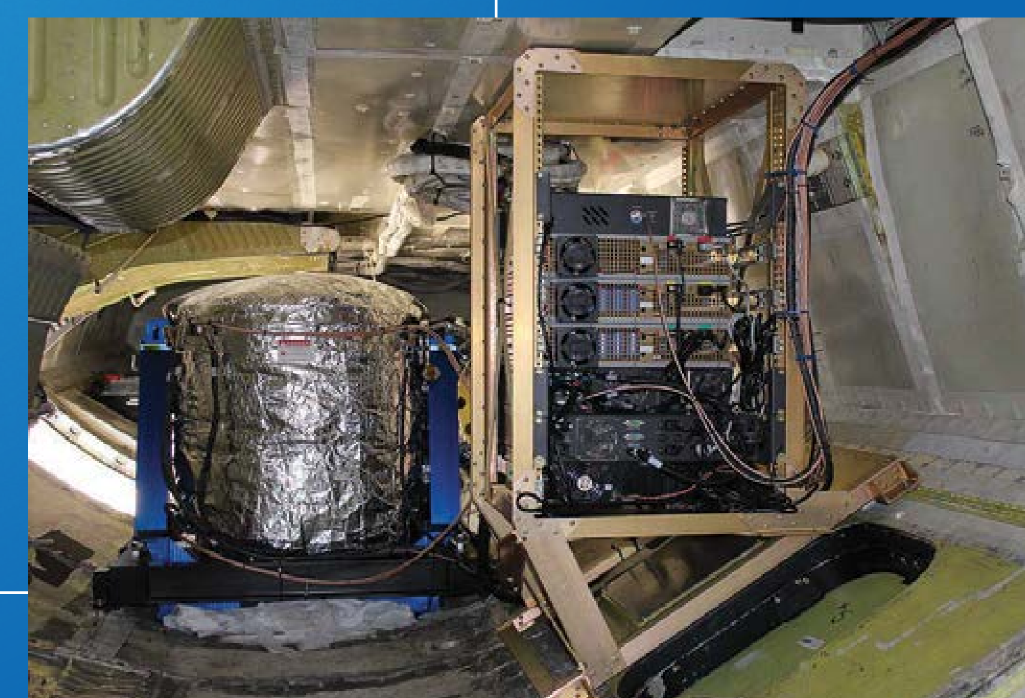
Several other science campaigns followed, including the 2017 NASA Convective Processes Experiment (CPEX) airborne campaign, which collected data over the Atlantic to study the lifecycle of convective storms. In 2019, DAWN flew in support of calibration/validation efforts of the European Space Agency's Aeolus mission, a wind-profiling satellite. In total, DAWN has completed over 500 flight hours onboard NASA's B-200 and DC-8 aircraft.

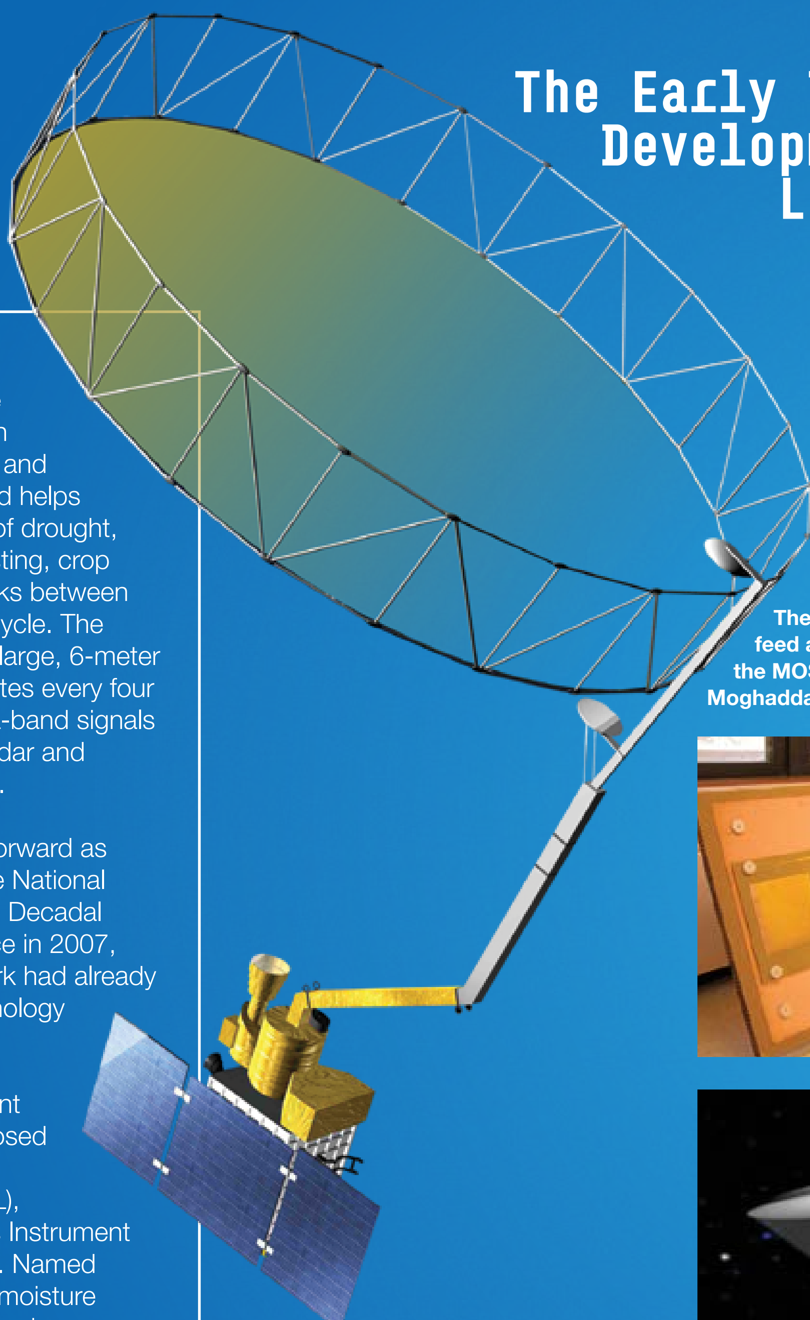
Mapping Wind Farm Sites

In September 2011, DAWN was also temporarily installed on the ground, in a trailer at the Fort Story military base on Virginia's coast, to assist the Virginia Coastal Energy Research Consortium (VCERC) in determining future offshore wind turbine locations. By scanning the beam up and down, the DAWN team was able to profile winds at various altitudes above the ocean surface corresponding to the height of a wind turbine. The data gathered during the month-long deployment was compared to in situ weather stations and used to determine which regions of the 140,000-acre offshore project contain the strongest, most consistent (and most valuable) winds.

A trailer containing DAWN positioned on a bluff at Fort Story, VA, overlooking the Atlantic Ocean Credit: G. Koch

The DAWN instrument mounted in the cargo bay of the NASA DC-8. Credit: NASA





The Early Technology Developments that Led to SMAP

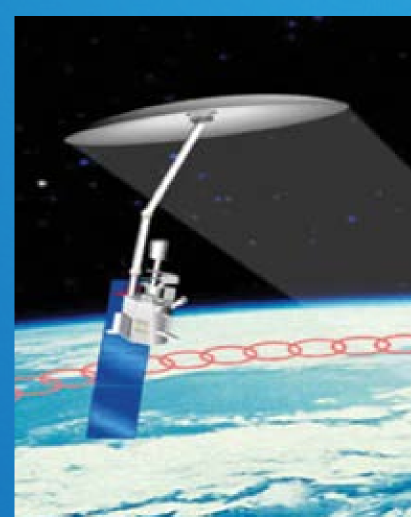
Launched in 2015, the Soil Moisture Active Passive (SMAP) mission measures soil moisture and freeze-thaw globally and helps aid our understanding of drought, floods, weather forecasting, crop productivity, and the links between water and the carbon cycle. The observatory includes a large, 6-meter mesh antenna that rotates every four seconds and focuses L-band signals back to the onboard radar and radiometer instruments.

When SMAP was put forward as a priority mission by the National Research Council's first Decadal Survey for Earth Science in 2007, much of the groundwork had already been laid by prior technology investments.

The SMAP measurement concept was first proposed by a 1998 study at the Jet Propulsion Lab (JPL), funded through ESTO's Instrument Incubator Program (IIP). Named the Ocean-salinity Soil-moisture Integrated Radiometer-radar Imaging System (OSIRIS), the study developed instrument performance requirements, designed radar and radiometer electronic subsystems, and designed antenna feeds and the rotating mesh reflector for a SMAP-like mission.

A second IIP project – Microwave Observatory of Subcanopy and Subsurface (MOSS), developed at the University of Michigan and JPL starting in 2002 – built and tested a prototype dual-frequency radar antenna feed system that, coupled with a 30-m mesh antenna, could enable 7-to-10-day repeat observations of subcanopy and subsurface soil moisture at 1 km resolution. A smaller version of the antenna design from this project later became the baseline for SMAP.

The full-scale dual-frequency feed array developed under the MOSS project. Credit: M. Moghaddam / University of Michigan



An early depiction of a SMAP-like mission, created by the Ocean-salinity Soil-moisture Integrated Radiometer-radar Imaging System (OSIRIS) project. Credit: E. Njoku / JPL

HIWRAP: Seeing Wind from Greater Heights

Completed in 2010, the High-Altitude Imaging Wind and Rain Airborne Profiler (HIWRAP) was developed at Goddard Space Flight Center to enable doppler radar from high-altitude aircraft, including uninhabited aerial vehicles (UAVs). The first unpressurized, high-altitude, solid-state Ka/Ku-band Doppler radar, HIWRAP was designed to measure tropospheric winds, particularly inside storms, and ocean surface winds.

Wind measurements are a crucial puzzle piece in the forecasting of tropical storms, and aircraft-borne Doppler radars have long been primary tools for measuring both horizontal and vertical winds inside rainy regions of these storms. However, standard aircraft have limited range, endurance, and altitude. Smaller, lighter, less power-hungry, and with no need for pressurization, HIWRAP can operate much higher in the atmosphere than previous airborne instruments.

Several technology developments – a compact dual-frequency antenna, solid state transceivers, a new pulse compression waveform, and a digital receiver – were key to these performance advantages and made HIWRAP an ideal payload for NASA's unique high-altitude aircraft.

Flying onboard NASA's ER-2 and WB-57 aircraft as well as the Global Hawk UAS, HIWRAP measures winds by analyzing the radar backscatter from clouds and rain drops. Much of the HIWRAP radar system rotates at about 10 rpm, enabling a three-dimensional view of the storms below.

To date, HIWRAP has logged nearly 1,400 flight hours and has participated in several airborne science campaigns, including: Genesis and Rapid Intensification Processes (GRIP), Hurricane and Severe Storm Sentinel (HS3), and Investigation of Microphysics and Precipitation for Coast-Threatening Snowstorms (IMPACTS).

Technicians install HIWRAP on the underside of a NASA Global Hawk in preparation for the GRIP campaign in 2010. Credit: Tony Landis / NASA

HOMER Laser Enabled GEDI, Aided MESSENGER Calibration

An artist's depiction of MESSENGER's Earth flyby. Credit: NASA / JHU-APL / Carnegie Institution

In 2014, an early ESTO-funded laser project at Goddard Space Flight Center – the High Output Maximum Efficiency Resonator (HOMER) – was selected to play a key role in NASA's Global Ecosystem Dynamics Investigation (GEDI) Mission.

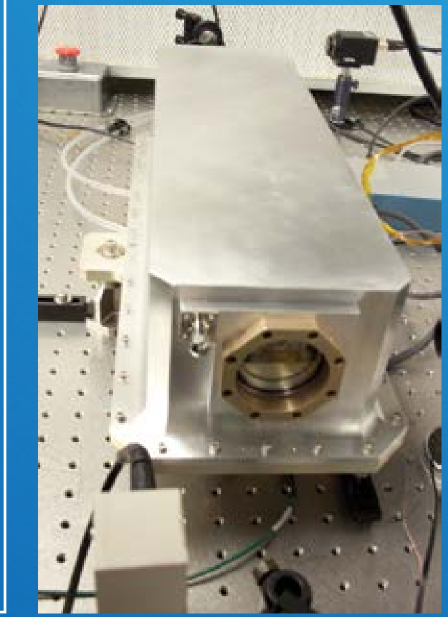
Launched to the International Space Station in December 2018, GEDI produced elevation profiles of Earth's forests to measure biomass, study habitats, and provided deforestation estimates for climate research. GEDI accomplished this using three HOMER laser transmitters to produce 12 parallel, 25-meter-wide tracks on the Earth's surface. The returning laser signals provided insight into the three-dimensional structure of vegetation within those swaths.

Work began on HOMER as early as 2003, with bench top development and extensive testing, including a multi-billion laser shot test. The laser was designed for efficient operation at 15-20 mJ with a minimum number of components to reduce flight risks for space-based remote sensing.

In May 2005, HOMER was also used to communicate with the Mercury Laser Altimeter (MLA) instrument aboard the MESSENGER spacecraft during an Earth fly-by. In orbit around Mercury, MLA provided high-precision mapping of topography from 2011 to 2015. The primary objective of the Earth fly-by tests was calibration of MLA: to determine instrument pointing, to verify laser characteristics, and to verify ranging system performance.

Installed at NASA's Goddard Geophysical and Astronomical Observatory in Maryland, HOMER exchanged laser pulses with MLA over approximately 15 million miles, a record distance for laser communication. The successful tests also marked the first back-and-forth exchange of laser signals between Earth and space (the Galileo probe received a one-way laser transmission from Earth at a distance of about 4 million miles in 1992).

The bench top HOMER laser in an air-tight enclosure, from 2005. Credit: D. B. Coyle / NASA



NeMO-Net: Resolving Coral Reefs

Coral reefs are essential for healthy oceans and thriving coastal communities. In the United States alone, coral reefs provide $100 billion worth of economic value and sustain more than 70,000 jobs, according to NOAA.

But this invaluable natural resource is dying out at an astonishing rate due to climate change. The United Nations Environment Programme estimates that as much as 90% of the world's coral could perish by 2050.

Ved Chirayath, who was a scientist at NASA's Ames Research Center at the time, used grants from ESTO's Advanced Information Systems Technology (AIST) program to pioneer breakthrough techniques for studying how climate change impacts coral reefs.

These awards helped fund "FluidCam," a compact sensor that allows researchers to see the ocean floor with unprecedented clarity, and "NeMO-Net," the first neural multi-modal observation and training network for global coral reef assessment.

Smaller than a football, FluidCam is a high-performance camera that captures detailed images of the seabed at depths of up to 45 feet. The instrument runs custom "Fluid Lensing" correction algorithms, which scrub distortion caused by the ocean surface from collected images.

FluidCam, developed in 2014, typically flies aboard a small airborne drone, but future iterations of the instrument could find their way onto spaceborne platforms, allowing researchers to observe coral reefs at a global scale.

NeMO-Net, developed in 2016, is a convolutional neural network that trains machine learning algorithms to classify coral reefs. The program features an innovative citizen science component, in which users play a mobile game to characterize sets of coral reef data that NeMO-Net then uses to improve its training regimen.

Now a National Geographic Explorer and Director of the Aircraft Center for Earth Studies at the University of Miami, Chirayath is working to apply his FluidCam, Fluid Lensing, and NeMO-Net technologies towards planetary science, combing images of distant planets for signs of extraterrestrial life.

A small drone equipped with FluidCam observes a coastal seabed. FluidCam, Fluid Lensing, and NeMO-Net provide researchers with clear, undistorted images of the ocean floor, making it easier to study coral reefs. Credit: Ved Chirayath / NASA Ames

RainCube and TEMPEST-D Instruments Infused into Upcoming INCUS Mission

Two ESTO-funded instruments – RainCube and TEMPEST-D – prototyped breakthrough technologies that paved the way for NASA's new Investigation of Convective Updrafts (INCUS) mission, which will help scientists better understand severe weather events.

INCUS will use three small satellites to collect novel data describing how convective storms cycle water and air through Earth's atmosphere. The third addition to NASA's Earth Ventures Mission portfolio, INCUS will allow scientists to observe the complex environmental factors that transform average convective storms into potent typhoons, cyclones, and hurricanes.

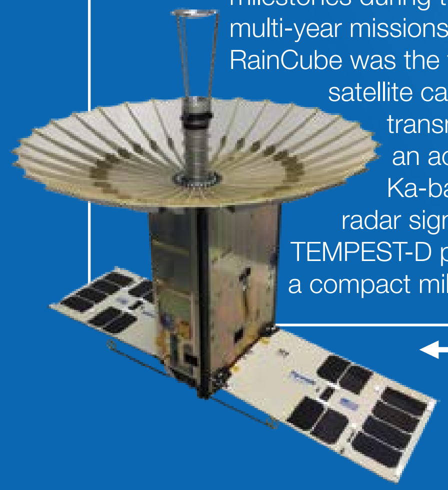
Small Ka-band radar systems and miniature millimeter wave radiometers capable of penetrating chaotic storm systems are essential to INCUS's success, and those systems first entered low Earth orbit as part of ESTO's RainCube and TEMPEST-D technology validation missions.

Launched in 2018, these 6U CubeSats achieved several milestones during their multi-year missions. RainCube was the first small satellite capable of transmitting an active, Ka-band radar signal, while TEMPEST-D pioneered a compact millimeter wave radiometer that could be used to monitor cloud and precipitation processes at a global scale.

In addition, RainCube's collapsible antenna became a key technology innovation, allowing for miniaturized active-sensing radar onboard small satellite platforms.

Data sets from RainCube and TEMPEST-D complimented each other. While RainCube gathered vertical profiles of severe storms with its active, scanning sensor, TEMPEST-D probed storms horizontally with its passive, 'push-broom' sensor. Combined, these data sets allowed researchers to observe the innermost areas of severe storms with unprecedented clarity.

Though both instruments have since deorbited – RainCube in 2020 and TEMPEST-D in 2021 – during their mission life they observed several high-profile storms, including Typhoon Trami, Hurricane Marco, Hurricane Laura, and Typhoon Surigae – one of the most powerful tropical cyclones in history.



Raincube with antenna deployed. Credit: JPL

TEMPEST-D shortly after release from the International Space Station. RainCube and TEMPEST-D pioneered novel technologies for observing severe weather, setting the stage for NASA's upcoming INCUS mission. Credit: NASA / ISS

CLARREO Pathfinder Benefits from a Breakthrough in Radiance Measurements

In August 2014, the HyperSpectral Imager for Climate Science (HySICS) instrument was carried aloft on a high-altitude balloon over New Mexico to make, at the time, the most accurate shortwave radiance measurements ever taken of Earth. During a nine-hour flight, HySICS took ultraviolet-to-solar radiance measurements of Earth, cross-calibrated by periodic measurements of the sun.

Outgoing radiance – the amount of sunlight reflected from Earth's surface and atmosphere and back to space – is a key measurement for climate studies, and measuring radiance over time helps quantify environmental changes. NASA satellites have collected radiance measurements of Earth for decades, but technology advances for the HySICS instrument are leading to measurements with higher accuracy than those currently available to researchers.

HySICS, which was developed at the University of Colorado Laboratory for Atmospheric and Space Physics (LASP) with funding by the Instrument Incubator Program (IIP), has a spectral range of 350 to 2300 nm, covering most of the sun's emitted energy. A single focal plane array spectrometer spans the entire wavelength range resulting in an instrument with reduced mass, volume, and power requirements.

The HySICS balloon test demonstrated radiometric accuracies of approximately 0.2%, nearly a 6x improvement over previous instruments. Such highly accurate, SI-traceable radiance measurements could enable faster detection of climate trends, on the scale of years instead of decades.

In 2016, the NASA Climate Absolute Radiance and Refractivity Observatory (CLARREO) Pathfinder mission team selected HySICS as its primary payload. When it is launched to the International Space Station, CLARREO Pathfinder will measure radiance from orbit with unprecedented accuracy and serve as a calibration reference for other satellite instruments.

The sun rises in Fort Sumner, NM, as the HySICS payload is readied for launch. Credit: NASA

A Sensor Web Approach for Soil Moisture

Members of the SoilSCAPE team inspect sensors at a field site in Happy Vally, Alaska. The spongy, uneven surface is known as thermokarst and made walking exceptionally difficult. Credit: K. Hines / NASA

From agriculture to weather prediction, accurate measurements of soil moisture content help answer a variety of questions, such as how water is stored and distributed in Earth's soils, how ecosystems function in variable conditions, and how the water cycle is globally regulated. With a series of awards from ESTO's Advanced Information Systems Technology (AIST) program, the SoilSCAPE project has helped provide answers while also supporting the calibration/validation activities of emerging airborne and space borne instruments.

SoilSCAPE – short for Soil moisture Sensing Controller And oPtimal Estimator – is a series of field sites, each consisting of dozens of wirelessly connected in-situ soil moisture sensors, installed in several U.S. states and New Zealand. These smart, low-power, autonomous sensor webs are designed to communicate with each other to adaptively and efficiently measure soil moisture at various depths. Following the installation of the first field site in Anne Arbor, MI, in 2007, at least 12 networks have been brought online, including in Oklahoma, Colorado, New Mexico, Arizona, Alaska, and California.

The SoilSCAPE sensor webs use guided and adaptive sampling strategies to conserve power when not needed and respond quickly to detected changes, ramping up data collection after a rainstorm for example. The SoilSCAPE sites feature a variety of surface and subsurface sensors, arranged in grids of nodes, with centralized controllers that task the nodes to take measurements as well as collect and forward their data. To aid in satellite calibration/validation, the sites are designed to measure soil moisture processes at a scale that mimics the ground footprints of remote sensing instruments in orbit.

During its first few years on orbit, the Soil Moisture Active Passive (SMAP) satellite, which launched in 2015, utilized a SoilSCAPE site in the eastern Sacramento Valley known as Tonzi Ranch for its calibration. The 150 sensor nodes spread over Tonzi Ranch's western savanna ecosystem of grassland, pine, and oak provided ground truth and aided in the modeling of complex hydrologic behavior.

Beginning in 2016, SoilSCAPE sites in Alaska also supported the Arctic-Boreal Vulnerability Experiment (ABoVE) field campaign, a multi-year airborne and ground-based science investigation to study the impact of climate change on ecosystems in the boreal and arctic regions of North America. More recently, SoilSCAPE sites in New Zealand have been setup to explore the sensitivity of Cyclone Global Navigation Satellite System (CYGNSS) satellite measurements to surface soil moisture and temperature.

SoilSCAPE is also part of the International Soil Moisture Network (ISMN), an international cooperative effort that maintains a global in-situ soil moisture database, an essential tool for land surface, climate, and hydrological modeling as well as for the validation of satellite data. SoilSCAPE data is used regularly by the scientific community, with 100s of user downloads every year through the ISMN web portal. More information on SoilSCAPE, including access to SoilSCAPE data, is available online at: soilscape.usc.edu

A sensor node at the Tonzi Ranch SoilSCAPE site in California. Credit: M. Moghaddam, USC

UAVSAR: A Workhorse Airborne Instrument for Earth Deformation Measurements

NASA's Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR), an airborne L-band radar developed at the Jet Propulsion Laboratory with funding from ESTO's Instrument Incubator Program (IIP), has become an invaluable airborne tool for solid Earth and glaciological sciences as well as disaster management.

While space-based assets can carry out deformation measurements of the Earth's surface, revisit times on the order of days to weeks limit their effectiveness in the study of rapidly changing features. Based on radar repeat pass interferometry, UAVSAR can conduct multiple flights over an area of interest within minutes, making surface deformation measurements to millimeter-level accuracy of earthquakes, volcanic deformation, forest and vegetation structure, ice, hydrology, and other natural processes.

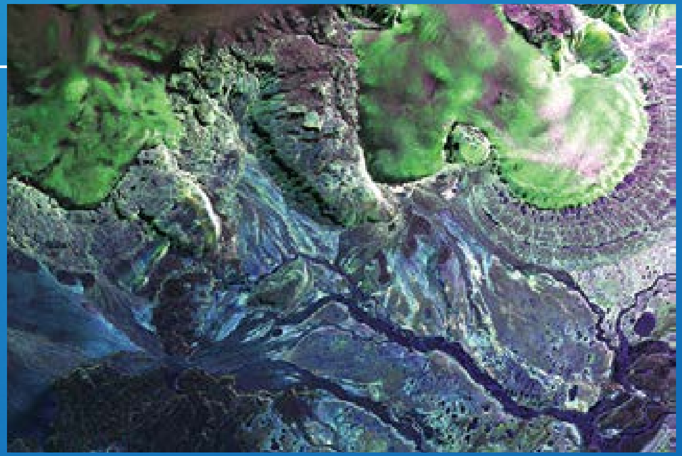
The early technology development of UAVSAR, which began in 2004, focused on two key challenges. First, repeat pass measurements needed to be taken from flight paths that are nearly identical. UAVSAR utilizes real-time GPS that interfaces with the airplane's flight management system to conduct the repeat flight to within the same 10 m path. Second, the radar vector from the aircraft to the ground target area must be similar from pass to pass. This is accomplished with an actively scanned antenna designed to support electronic steering of the antenna beam with 1° increments over a range of ± 15° in the flight direction.

Now a 'facility-class' instrument, UAVSAR has logged over 300 flights since 2008 and is the most-requested airborne tool in NASA's portfolio. Many of these flights directly supported disaster response efforts, such as mapping faults following earthquakes in Haiti (2010), imaging the Deepwater Horizon oil spill (2010), analyzing sinkholes in Louisiana (2014), and studying landslide dangers in California (2019).

UAVSAR has also participated in numerous airborne campaigns, including SnowEx, Delta-X, Arctic-Boreal Vulnerability Experiment (ABoVE), and Oceans Melting Greenland (OMG). Additionally, several space missions – such as NASA-ISRO SAR (NISAR), Soil Moisture Active Passive (SMAP), and Ice, Cloud and land Elevation Satellite (IceSat-2) – have utilized UAVSAR for formulation and calibration/validation activities.

The UAVSAR pod hangs below the belly of NASA's Gulfstream III at the Armstrong Flight Research Center. The four vents around the pod are used to air-cool the radar equipment during flight. Credit: Dave Bullock / Wired.com

Polarimetric image of Hofsjokull, Iceland, taken by UAVSAR in June 2009. The blue areas are bare ground surfaces and the green areas are ice. Credit: NASA



Multi-sensor Data Synergy Advisor: Making Sense of Complex Data Sets

Merging data sets collected by different instruments and stored within different file structures can be like mixing oil and water, but creating these data infusions is essential for building comprehensive, nuanced descriptions of complicated Earth systems.

In 2008, a team of ESTO-funded NASA scientists began developing a new software tool for combining unique data sets more efficiently. Their project, the "Multi-sensor Data Synergy Advisor (MDSA)," automatically identified potential relationships between disparate data sets, greatly reducing the amount of time it took researchers to turn raw information into complete science products describing tremendously complex phenomena like climate change.

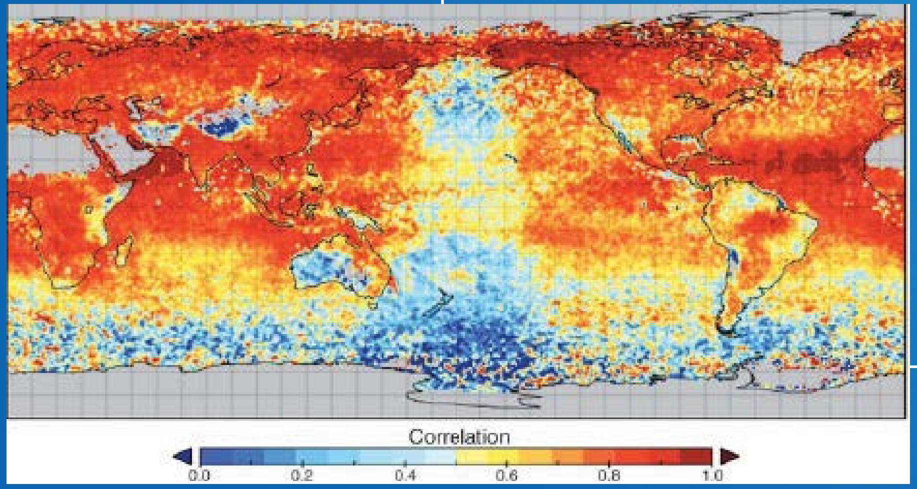
Led by Gregory Leptoukh, a NASA Science Data Manager, and Christopher Lynnes, a NASA Data Systems Architect, the research team successfully codified ontology parameters in such a way that computers could find similarities between data sets regardless of how those data sets were formatted or stored.

Their ontological technique was a novel, user-friendly technology innovation that made it much easier for scientists to incorporate data sets from numerous disciplines and missions into their research.

An atmospheric chemist, for example, interested in studying the impact air pollution might have on ocean acidification, could use the MDSA to synthesize a single data product that correlates air quality data gathered by one instrument with marine water quality data gathered by another.

In 2011, Leptoukh and Lynnes successfully transferred the MDSA to the Goddard Earth System Data and Information Services Center, where it became a software augmentation for Giovanni – one of NASA's data access and visualization portals. In addition, components of the project eventually became independent products. The MDSA "Semantic Advisor" helped researchers improve NASA's Distributed Active Archive Center and allowed scientists to better incorporate ozone measurements into NASA's Atmospheric Composition Portal.

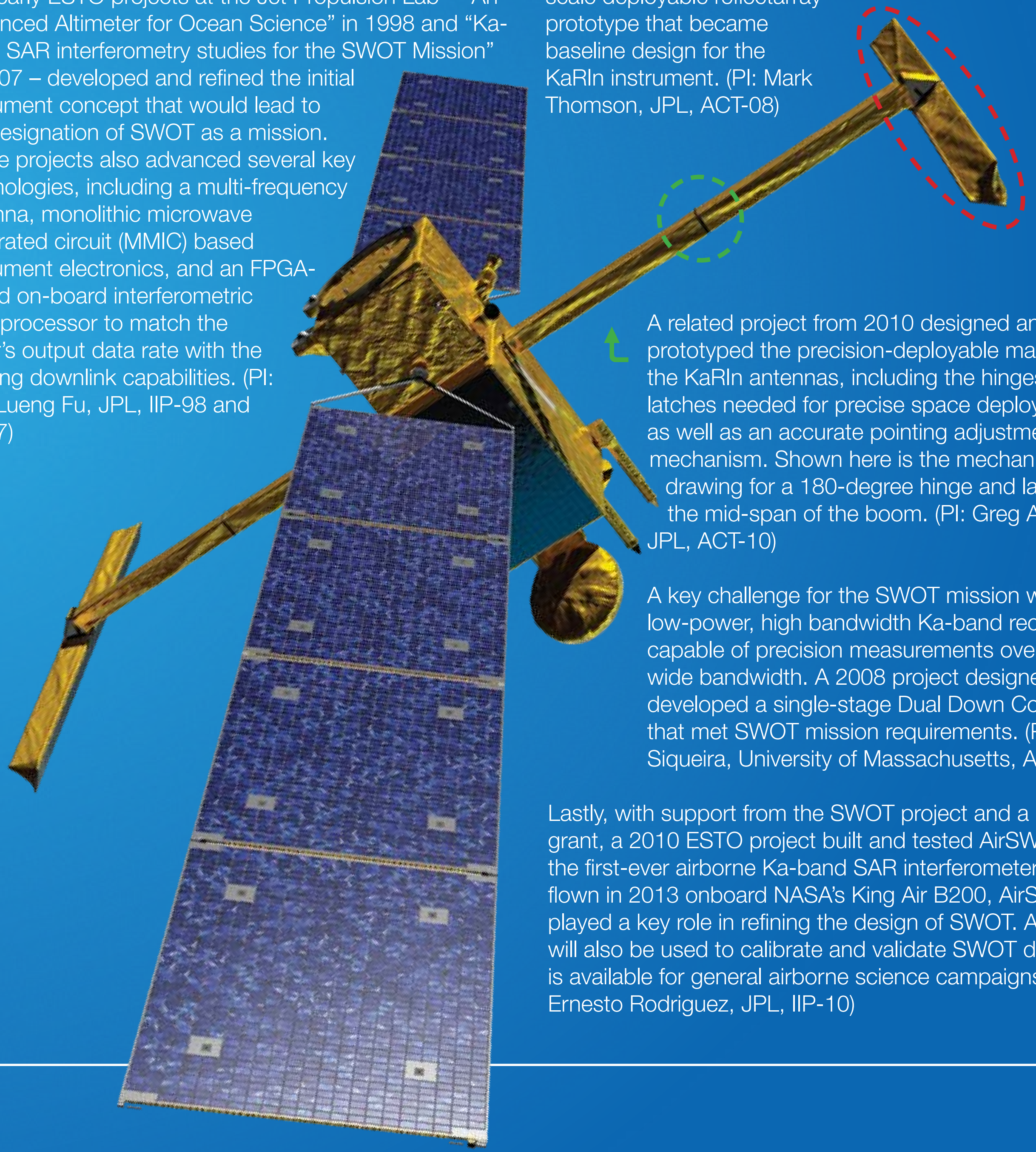
A data visualization generated with the MDSA, which shows a zero-correlation anomaly centered on the international date line. Data visualizations like this one make it easier for researchers to understand cause-and-effect relationships between complex data sets. Credit: P. Fox / Science



Early Technology Developments for the SWOT Mission

Launched in December 2022, the Surface Water Ocean Topography (SWOT) mission is intended to produce a better understanding of the world's oceans and terrestrial surface waters at a much higher spatial resolution than is currently available. Using wide-swath radar altimetry measurements, SWOT will make the first global survey of Earth's surface water, observe the fine details of the ocean's surface topography, and measure how water bodies change over time.

Since 1998, numerous ESTO investments have steadily advanced the technologies needed for such a mission. Two early ESTO projects at the Jet Propulsion Lab – "An Advanced Altimeter for Ocean Science" in 1998 and "Ka-band SAR interferometry studies for the SWOT Mission" in 2007 – developed and refined the initial instrument concept that would lead to the designation of SWOT as a mission. These projects also advanced several key technologies, including a multi-frequency antenna, monolithic microwave integrated circuit (MMIC) based instrument electronics, and an FPGA-based on-board interferometric SAR processor to match the radar's output data rate with the existing downlink capabilities. (PI: Lee-Lueng Fu, JPL, IIP-98 and IIP-07)



SWOT includes two deployable, 5-m, Ka-band reflectarray antennas – part of the Ka-band Radar Interferometer (KaRIn) on SWOT – that are separated by 10 m. These antennas need to be structurally flat and thermally stable to meet demanding pointing and interferometric phase stability requirements. A 2008 project at the Jet Propulsion Lab built and tested a full-scale deployable reflectarray prototype that became baseline design for the KaRIn instrument. (PI: Mark Thomson, JPL, ACT-08)

A related project from 2010 designed and prototyped the precision-deployable masts for the KaRIn antennas, including the hinges and latches needed for precise space deployment as well as an accurate pointing adjustment mechanism. Shown here is the mechanical drawing for a 180-degree hinge and latch at the mid-span of the boom. (PI: Greg Agnes, JPL, ACT-10)

A key challenge for the SWOT mission was a low-power, high bandwidth Ka-band receiver capable of precision measurements over a wide bandwidth. A 2008 project designed and developed a single-stage Dual Down Converter that met SWOT mission requirements. (PI: Paul Siqueira, University of Massachusetts, ACT-08)

Lastly, with support from the SWOT project and a SBIR grant, a 2010 ESTO project built and tested AirSWOT, the first-ever airborne Ka-band SAR interferometer. First flown in 2013 onboard NASA's King Air B200, AirSWOT played a key role in refining the design of SWOT. AirSWOT will also be used to calibrate and validate SWOT data and is available for general airborne science campaigns. (PI: Ernesto Rodriguez, JPL, IIP-10)

Early Technology Developments for the NISAR Mission

The NASA-ISRO SAR (NISAR) mission, slated to launch in January 2024, is a joint effort between NASA and the Indian Space Research Organization (ISRO) that will measure a broad range of features on Earth's surface, from glaciers and ice sheets to the dynamics of earthquakes and volcanoes.

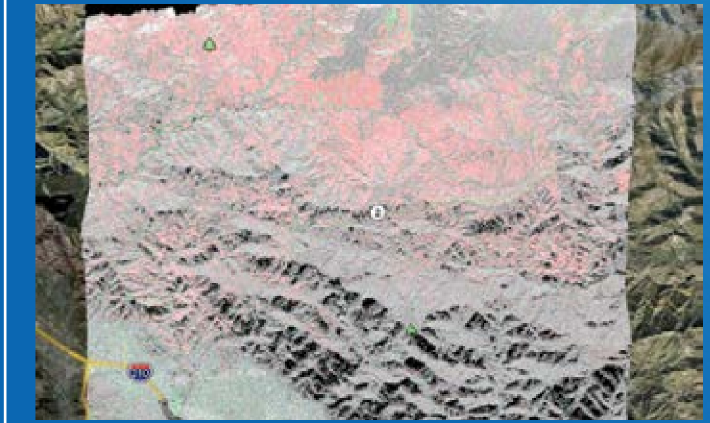
To make these measurements, NISAR will collect data in two microwave bandwidth regions: L-band and the S-band. NASA is providing the mission's L-band synthetic aperture radar, a high-rate communication subsystem for science data, GPS receivers, a solid-state recorder and payload data subsystem. ISRO is providing the spacecraft bus and the S-band radar as well as the launch.

Several ESTO projects have helped pave the way for NISAR:

UAVSAR

An airborne precursor to NISAR, the Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) instrument informed NISAR in several ways. The NISAR L-band radar feed aperture and its corresponding RF distribution network are based on the UAVSAR design. NISAR has also adapted UAVSAR's transmit beamformer network design, power supply design, and controller design. UAVSAR will also serve as a calibration-validation platform for NISAR. PI: Scott Hensley, JPL // 2003 IIP Award

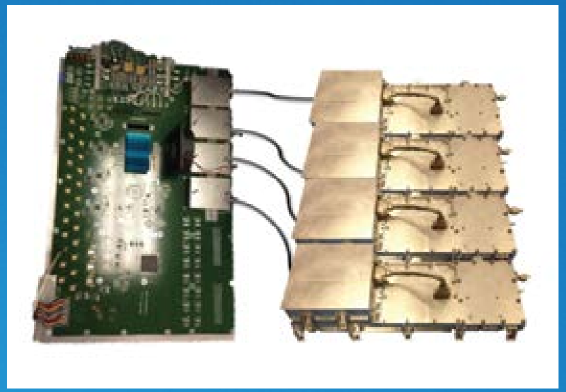
From 2014, the UAVSAR radar pod mounted below the NASA Gulfstream-III jet. Credit: JPL



Processed, composited UAVSAR data from the Station Fire burn scar in the Angeles National Forest from 2009. Vegetated areas shown in red, non-vegetated areas shown in green, with repeat pass change in backscatter > 3 dB. Credit: Yunling Lou / JPL

On-Board Data Processing

A 2008 information systems technology award has helped inform NISAR mission strategies for onboard processing and autonomous data acquisition. Originally intended to support the DESDynI mission concept, the L-Band SAR Onboard Processing project developed new FPGA-based data processing hardware with autonomy-enabled software to perform data acquisition on-demand. The system was demonstrated on UAVSAR flights, reducing downlink data volume by a factor of 10 or more.
PI: Yunling Lou, JPL // 2008 AIST award



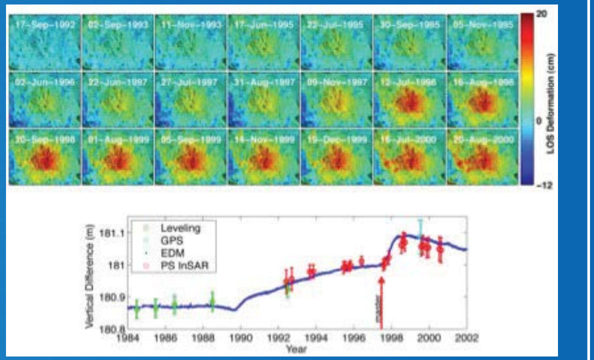
NISAR's T/R module assembly consisting of the quad-channel first-stage processor and four digitally calibrated T/R modules. Credit: James Hoffman / JPL

T/R Modules

Beginning in 2002, a series of component technology projects developed the sophisticated Transmit/Receive (T/R) modules needed for a spaceborne L-band radar. These efforts produced the overall module design, digital calibration techniques, and the high-power amplifier that were adopted by the NISAR mission.
PI: Wendy Edelstein and James Hoffman, JPL // 2002, 2005, 2008, and 2010 ACT awards

Computing

The Integrated InSAR Scientific Computing Environment (iISCE) is a cloud-based SAR processing framework that will provide a number of tools for the processing of NISAR data, including the production of image data, interferometric and polarimetric processing, science algorithms for specific use cases, and calibration/validation. Developed and tested on existing radar instrument data, iISCE's functionalities will be available for scientists to interrogate NISAR data, either on local computing devices or through cloud services.
PI: Paul Rosen, JPL // 2008 and 2011 AIST awards



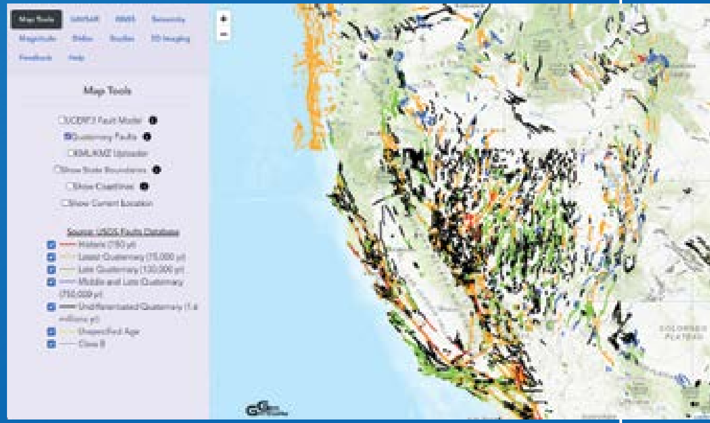
This time series of images from 2013 depict the decadal-long uplift of Long Valley Caldera near Mammoth, California due to magma below the surface. Courtesy H. Zebker / Stanford University.

An artist's depiction of multi-satellite Smart Tasking system. Credit: K. Jones / JPL

Smart Tasking

The Smart Tasking disaster response system, a prototype urgent response tasking request system suitable for use by multiple NASA spaceborne missions, has been adopted by the NISAR Mission System as the interface for rapidly evolving hazards. Managed by the NISAR Science Data System, the Smart Tasking system enables full automation of request processing and instrument retaking, and could be extended to support multiple missions or satellite constellations. PI: Kathleen Jones, JPL // 2019 AIST award

A view of the GeoGateway map tool showing Quaternary faults in the western U.S. Credit: GeoGateway



Data Analysis

GeoGateway, formerly known as QuakeSim, is a web-based science gateway that provides tools for scientific discovery, field use, and disaster response using Interferometric SAR (including from UAVSAR) and Global Positioning System data integrated with earthquake faults data sets, seismicity data, and models. GeoGateway products are widely used – by the US Geological Survey, the State of California, and others, as well as by academic researchers – to access, analyze, and interpret geodetic data, and the system is poised to take advantage of NISAR mission data. PI: Andrea Donnellan, JPL // 2005, 2008, and 2011 AIST awards

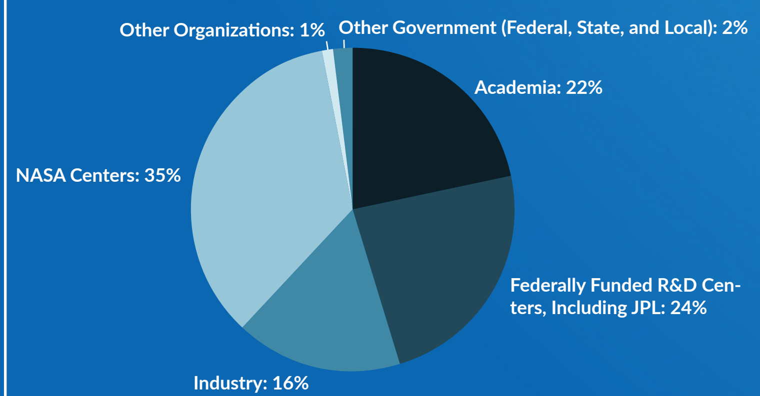
By the Numbers: 25 Years of Programmatic Metrics

What follows are a few of the notable metrics of the ESTO portfolio from the last 25 years. From technology advancement and infusions to publications and patents ESTO projects have made significant impacts to NASA and beyond. In 2023, ESTO initiated a comprehensive retrospective study to further catalog and verify past achievements, particularly from early investments. While that effort is likely to add to several of the tallies below, these metrics demonstrate the remarkable success of early technology development through a competitive, peer-review selection process.

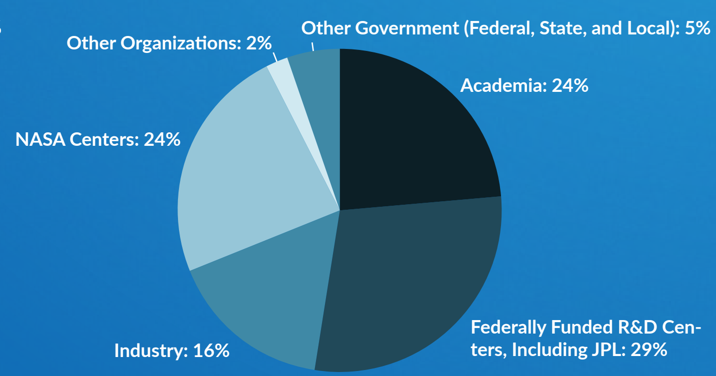
A Diversified Portfolio

ESTO technology projects find their origins in a wide range of people and institutions across the country. Principal investigators hail from more than 200 different organizations – from colleges and universities to corporations and non-profits to NASA field centers and Federal labs – in 42 states. More than 2,000 collaborators, co-investigators, and other partners also contribute their expertise, from over 400 organizations in 44 states. In response to the 44 solicitations ESTO has released since 1998, this community of technologists, engineers, and scientists has supplied an abundance of new ideas and methods for NASA Earth science endeavors.

Principal Investigator Institutions

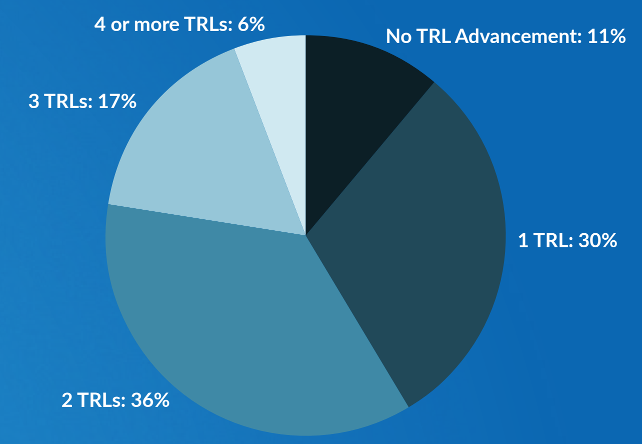


Co-Investigator/Partner Institutions

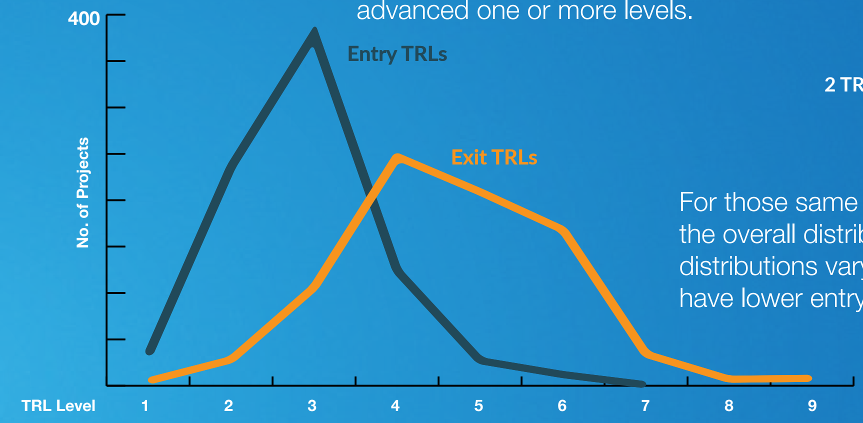


Measuring Advancements

For the vast majority of projects in its portfolio, ESTO makes regular assessments of Technology Readiness Levels (TRLs), including at the outset of the project, annually during the period the period of performance, and at the project's final review. An analysis of all TRL-reportable projects that have graduated from ESTO funding yields an impressive picture of advancement:



Of the 812 projects that have graduated from ESTO funding and were assessed for TRL, nearly 90% advanced one or more levels.



For those same 812 completed projects, this chart shows the overall distribution of start and end TRLs. Note that TRL distributions vary by ESTO program area; components generally have lower entry and exit TRLs than instruments, for example.

Infusions

ESTO principal investigators have reported at least 269 infusions of their technologies into Earth science missions, science campaigns, and other operational or commercial activities. Below is the breakout of verified infusions since 1998:

- **65 Projects** infused into Earth science flight missions, at NASA and other agencies
- **43 Projects** infused into non-Earth science flight missions, at NASA and other Agencies
- **44 Projects** infused into NASA Earth Venture (EV) activities (79% of Earth Venture selections include ESTO heritage)
- **52 Projects** infused into airborne science campaigns, at NASA and other organizations
- **56 Projects** infused into NASA Distributed Archive Data Centers or other data access/ modeling systems, including at other organizations
- **9 Projects** transitioned to commercial applications

Further, several hundred projects have transitioned to other NASA programs, other Federal agencies, SBIR awards, or internal funding through the originating organization.

Publications & Presentations

Just as with basic science research, the sharing of ideas, advancements, and findings is crucial to the advancement of technology. ESTO projects have produced well over 600 peer-reviewed journal articles as well as more than 2,500 conference presentations. ESTO has also hosted a nearly annual conference starting in 2001, and now known as the Earth Science Technology Forum, which presents an opportunity for principal investigators to further showcase their work. Over the 19 iterations of this event held during the last 23 years, some 1,300 presentations have been given to more than 5,000 attendees.

Patents

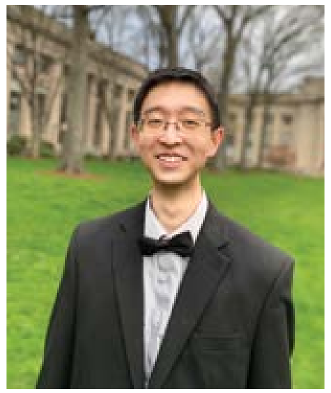
At least 23 patents have been issued for ESTO technologies, including one during FY23:

Patent Number: US 11,493,602 B1; Issued: 11/08/2022

Integrated Multi-Wavelength WDM (Wavelength Division Multiplexing) TDM (Time Division Multiplexing) Lidar Transmitter. Guangning Yang and Jeffrey Chen, NASA Goddard Space Flight Center

STUDENT SPOTLIGHT

As with many research and development activities, students are integral to the work and success of technology development teams. Since ESTO's founding, at least 1,180 students from 171 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 FY23 alone, at least 157 students from 48 institutions were involved with active technology development projects.



Alex Wang

Alex Wang is pursuing a master of engineering at MIT. His specialty is Computer Science and Engineering, especially machine learning. He made major contributions to two ESTO-funded AIST projects this past year, training and modifying the FourCastNet model with MERRA-2 reanalysis data to allow for computationally efficient sampling of atmospheric states. When he's not busy with work, Alex likes to go on runs, and he also enjoys playing piano and viola.

Kate Bartlett

Kate Bartlett is a senior at the University of Michigan, where she studies climate and computer science. Kate built the 'Reporter' component of ILEOS, an ESTO-funded project that optimizes flight paths for HALE vehicles. Kate also added constraints to refine the 'Planner' component of ILEOS, which is an essential part of the flight path optimization process. When she's not applying to PhD programs in climate dynamics and atmospheric modeling, Kate likes to write, spend time outside, and scuba dive.

Bruno Mattos

Bruno Mattos is a fourth-year PhD student at Utah State University, where he specializes in space-based remote sensing. Specifically, he's developing FINIS, a compact, shortwave infrared spectrometer designed to detect methane plumes from space. His instrument prototype will fly aboard ACMES, an InVEST-funded technology validation mission. Bruno also contributed to HyTI, another InVEST project dedicated to studying volcanoes. When he isn't producing innovative science, Bruno enjoys flying drones and playing with his four-year-old daughter.

Benjamin Nold

Benjamin Nold just completed a PhD at Purdue University, where he specialized in instrument design, analysis, simulations, and calibration. Working with ESTO-investigator James Garrison, he designed and built a ground-based monitoring station for SNOOPI, an InVEST-funded 6U CubeSat that will measure soil moisture. In addition, Benjamin worked as a Pathways engineer on the CubeSat bus that will eventually carry SNOOPI into orbit. Now a staff engineer at NASA's Goddard Space Flight Center, Benjamin enjoys distance running and playing the pipe organ for his church.

Michael McPherson

Michael McPherson is a second year master's student in the Howard University Program on Atmospheric Sciences. His research interests include high altitude instrumentation, space debris re-entry, and the affects that debris has on Earth's atmosphere. Michael conducted a thermal analysis of a cooling loop system for A-SMLS, an ESTO-funded, airborne microwave scanning instrument for studying atmospheric chemistry. He also helped develop and integrate sensors into the instrument's thermal control loop. In his free time, Michael cooks, reads, and watches movies.

Brandon Mitchell

Brandon Mitchell is a fourth-year PhD student at the University of Arizona, where he specializes in hydrometeorology and space-based remote sensing – particularly lidar. His unique expertise was a tremendous asset to PI Carl Weimer, whose IIP-funded team is developing a quantum lidar system for measuring the depth of snowpacks. Brandon attributes his interest in flood events and their societal impacts to his childhood in New Orleans. In his free time, Brandon enjoys cheering for the New Orleans Saints and playing rugby.

Shaurya Pathak

Shaurya Pathak is a rising junior at the University of California, Riverside, where he studies Computer Science. For the past two years, he's helped PI Mohammad Pourhomayoun develop an AIST project for predicting and estimating air pollution levels in Los Angeles. Specifically, Shaurya is developing a "Digital Twin of Air Mobility" to better understand how air taxis can positively impact air pollution. He likes to play chess and pick-up basketball in his free time.

Sierra Dahiyat

Sierra Dahiyat is a junior at the University of California, Berkeley, where she studies Data Science. Sierra supports "EcoPro," an AIST-funded project to help researchers better understand how human behavior and climate change impact biodiversity. Specifically, Sierra helped train and test regression models, which could one day forecast how kelp forests will respond to climate change. Her hobbies include dancing, Pilates, and skiing.

Benjamin Lewis

Benjamin Lewis recently finished a master's degree at Utah State University, where he will also earn his PhD. His specialty is signal processing algorithms for field programmable gate arrays. As an undergraduate, he helped develop the preliminary systems for the InVEST-funded ACMES project, and in graduate school, he's helped develop the PLAID instrument – a planar radio-frequency impedance probe that will fly aboard ACMES. In addition to working with space-based instruments, Benjamin also enjoys working with musical instruments. He plays the guitar, the piano, and the organ.

Pratyush Muthukumar

Pratyush Muthukumar is a graduate student at Stanford, where he's finishing a master's degree in Computer Science. Working with ESTO-investigator Mohammad Pourhomayoun, the 19-year-old researcher developed cutting-edge models for "Predicting What We Breathe," an AIST-funded project that forecasts ground-level air pollution in urban environments. In his free time, Pratyush enjoys playing sports and spending time with his friends and family.

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