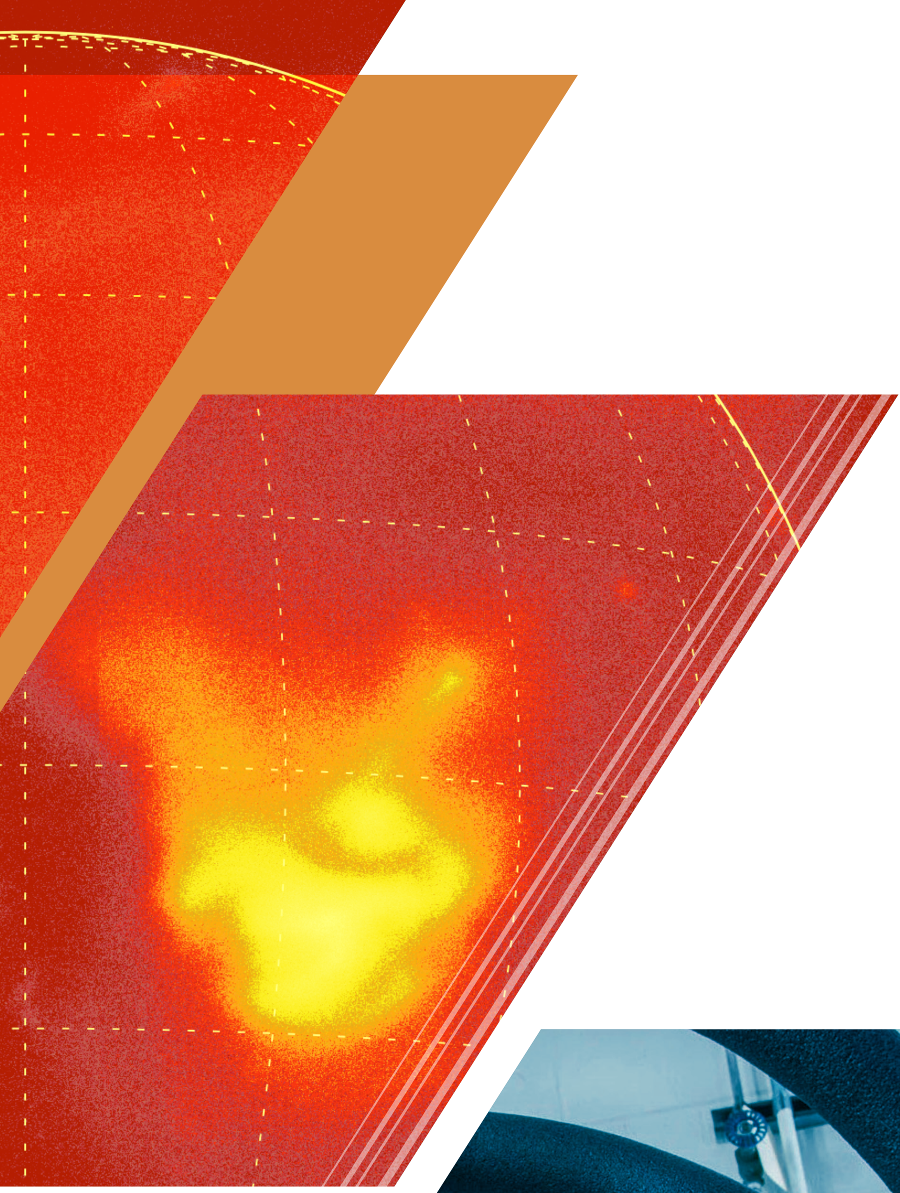
National Aeronautics
and Space Administration

SCIENCE MISSION DIRECTORATE

TECHNOLOGY HIGHLIGHTS

2018



ENABLING GROUNDBREAKING SCIENCE THROUGH TECHNOLOGICAL INNOVATION...

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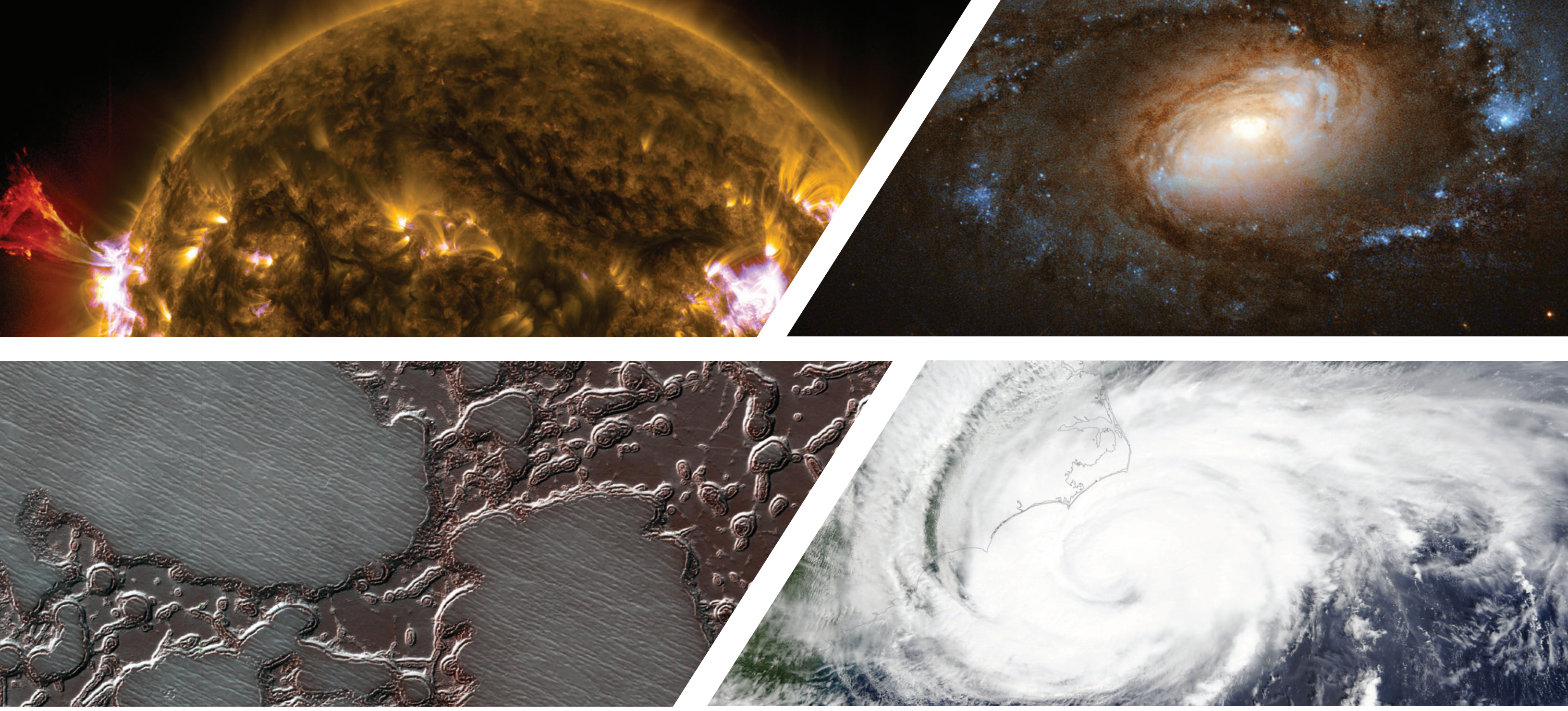


▶ Clockwise from upper left: Composite image of the Sun from NASA's Solar Dynamics Observatory; spiral galaxy NGC 4102, observed by the Hubble Space Telescope; September 2018 image from NASA's Terra satellite of Hurricane Florence as it approached the eastern coast of the U.S.; image of dry ice at the Mars south pole from the Mars Reconnaissance Orbiter.

INTRODUCTION

No doubt you have seen intriguing images of faraway galaxies, photos of distant planetary surfaces, and images of the Sun and Earth like those above. These images are obtained through NASA science endeavors that not only allow us to learn about how the universe, our solar system, the Sun, and Earth function and influence one another, they enable us to use this knowledge to impact and improve life on Earth. But acquiring this scientific knowledge often requires significant technological innovation beyond the state of the art. NASA's Science Mission Directorate (SMD) sponsors the cutting-edge technology development efforts that enable the research programs and complementary missions that produce this groundbreaking science.

SMD accomplishes technology development via programs established in its four divisions—Astrophysics, Earth Science, Heliophysics, and Planetary Science (see table on pages 2-3). SMD coordinates technology development efforts among its divisions, formulating joint projects where common needs exist. We also coordinate with other Agency organizations to ensure NASA's technology development endeavors meet Agency and National goals. In addition, SMD communicates with industry, academia, and other agencies to take advantage of any relevant technologies they have to offer.

This year's annual report highlights a number of significant SMD technology development efforts that will enable NASA's future science endeavors. In addition, this report features entries about SMD technology management and planning, including an article on the formulation of a new technology-focused organization in the Planetary Science Division and an entry on the recent SMD workshop on autonomy. An overview of the SMD technology strategy is available in the appendix.

I hope you enjoy reading this issue and learning about several of the important SMD investments that will help guarantee the advancement of NASA science.

Sincerely,

Michael Seablom
NASA Science Mission Directorate
Chief Technologist

SMD TECHNOLOGY DEVELOPMENT PROGRAMS

EARTH SCIENCE DIVISION (FUNDED AND MANAGED THROUGH THE EARTH SCIENCE TECHNOLOGY OFFICE, ESTO)	
Advanced Component Technologies (ACT)	Develops a broad array of component and subsystems technologies to reduce the risk, size, cost, mass, and development time for future Earth science instruments and observing systems.
Instrument Incubator Program (IIP)	Develops and demonstrates new measurement technologies, which significantly reduce the risk, size, cost, mass, and development time for future Earth science instruments and observing systems.
Advanced Information Systems Technology (AIST)	Develops and supports the adoption of advanced information technology for acquiring, processing, accessing, visualizing, and communicating Earth science data.
In-Space Validation of Earth Science Technologies (InVEST)	Enables on-orbit technology flight validation and risk reduction for small instruments and new measurement concepts through spaceborne demonstrations.
Airborne Instrument Technology Transition	Enables mature instruments and systems to be rapidly put into operational service in airborne field campaigns, collecting science data, validating satellite observations, and evaluating new satellite instrument concepts.
Sustainable Land Imaging Technology (SLI-T)	Develops innovative technologies to achieve future sustainable land imaging (Landsat) measurements with more efficient instruments, sensors, components and methodologies.
Decadal Science Incubation (DSI)	Matures observing systems, instrument technology, and measurement concepts for Planetary Boundary Layer and Surface Topography and Vegetation observables through technology development, modeling/system design, analysis activities, and small-scale pilot demonstrations.
HELIOPHYSICS DIVISION	
Sounding Rockets and Range Program	Develops new sounding rocket and range technologies; serves as a low-cost testbed for new scientific techniques, scientific instrumentation, and spacecraft technology eventually flown on satellite missions.
Heliophysics Technology and Instrument Development for Science (H-TIDeS)	Supports basic research and development of new technologies and scientific instruments; includes feasibility demonstrations that may enable future science missions.
Heliophysics Flight Opportunities for Research and Technology (H-FORT)	Orbital and suborbital flight opportunities for feasibility demonstration of technologies and scientific instruments, as well as scientific investigations involving significant level of technology development.
PLANETARY SCIENCE DIVISION	
Planetary Instrument Concepts for the Advancements of Solar System Observations (PICASSO)	Develops low Technology Readiness Level (TRL) technologies to enable new planetary science observing instruments, sensors and in situ systems.
Maturation of Instruments for Solar System Exploration (MatISSE)	Matures planetary science instruments to the point where they may be proposed in response to future announcements of flight opportunity without additional extensive technology development.

SMD TECHNOLOGY DEVELOPMENT PROGRAMS, CONT...

Development and Advancement of Lunar Instrumentation (DALI)	Develops lunar science instruments suitable for small lunar landers, including those of commercial providers.
Lunar Surface Instrument and Technology Payloads (LSITP)	Develops science and exploration instruments, sensors, and in situ system technologies into flight payloads for commercial lunar landers.
Hot Operating Temperature Technology Program (HOTTech)	Develops technologies for the robotic exploration of high-temperature environments, such as the Venus surface, Mercury, or the deep atmospheres of Gas Giants.
Concepts for Ocean Worlds Life Detection Technology (COLDTech)	Develops spacecraft-based instruments and technology for surface and subsurface exploration of ocean worlds such as Europa, Enceladus, and Titan.
Scientific Exploration Subsurface Access Mechanism for Europa (SESAME)	Develops technologies to help define and validate system concepts for deep subsurface ice access for ocean worlds.
Instrument Concepts for Europa Exploration (ICEE)	Develops scientific instruments and sample transfer mechanisms for Europa surface exploration.
Astrodynamics in Support of Icy Worlds Missions (ADYN)	Develops the formulation, maturation, and validation of new astrodynamics analysis tools.
Radioisotope Power System Program (RPSP)	Strategically invests in nuclear power technologies to maintain NASA's current space science capabilities and enable future space exploration missions.

ASTROPHYSICS DIVISION

Astrophysics Research and Analysis (APRA)	Supports basic research of new technologies (TRL 1-3) and feasibility demonstrations; includes science investigations on suborbital flights that often involve a significant level of technology development.
Strategic Astrophysics Technology (SAT)	Supports the maturation of technologies whose feasibility has been demonstrated (i.e., TRL 3) to the point where they can be incorporated into NASA flight missions (TRL 6-7). All three science themes within the Astrophysics Division (the Physics of the Cosmos Program [PCOS], the Cosmic Origins Program [COR], and the Exoplanet Exploration Program [ExEP]) are within the scope of the SAT Program.
NASA Balloon Program	Provides high-altitude platforms for scientific and technological investigations and for demonstrations of promising new instrument and spacecraft technologies that will enable or enhance SMD objectives.
Roman Technology Fellowships (RTF)	Provides opportunities for early-career astrophysics technologists to develop the skills necessary to lead astrophysics flight instrumentation development projects. Develops innovative technologies that enable or enhance future astrophysics missions.

▶ Salvatore Oriti and Scott Wilson inspect power converter TDC #13 in NASA GRC's Stirling Research Laboratory.

RECORD SETTING POWER SYSTEM DISASSEMBLED AND ANALYZED: PROVES VIABILITY OF POWER TECHNOLOGY

PROJECT:
Dynamic Radioisotope Power Systems (DRPS)

SPONSORING ORGANIZATION:
Planetary Science Division's Radioisotope Power Systems Program

KEY POINTS:
Understanding potential failure modes can lead to improved designs that will enable Dynamic RPS to provide highly reliable power to planetary science missions for up to 17 years of operational life.

Future NASA missions to the Moon, Mars, the outer planets and their moons, and beyond will need long-lived, reliable power. The Dynamic Radioisotope Power Systems (DRPS) Project is maturing technology that will provide hundreds of watts of continuous electrical power for long duration missions.

In 2003, DRPS free-piston Stirling convertor prototypes were fabricated and began operation at the NASA Glenn Research Center (GRC) to demonstrate long life. Two of these units, Technology Demonstration Convertors (TDC) #13 and #14, operated for many years without the need for parts or maintenance. The GRC team evaluated the TDCs and found no performance degradation, which shows these units have the reliability necessary for a long-life dynamic power convertor.

In May 2017, after 12 years (105,616 hours) of operation, NASA decided that TDC #14 would be taken offline to determine what modes of deterioration, if any, were occurring within the convertor. Its twin, TDC #13, was detached from TDC #14, returned to operation, and continues to set a world record for the longest running engine, now exceeding 117,000 hours, as of the end of April 2019.

In 2018, the GRC team completed the disassembly and examination of TDC #14. The results show normal operation, with no sign of fatigue or material creep, despite evidence of scratches and small amounts of debris (due to imperfect sealing) discovered near close-clearance seals. The close-clearance seal dimensions and alignment were stable over 12 years of operation. Also, while there was some early oxidation of parts prior to hermetic welding of the joints, components were not compromised. Oxygen ingress can be prevented in future systems. This examination shows that long-lived dynamic radioisotope power systems (RPS) can be can be available for future space science and exploration missions.

▶ Team members inspecting a 20 cm atomic layer deposited microchannel plate (left). Cross strip imaging readout anode (right).

CROSS STRIP PHOTON COUNTING SENSORS — PATHWAY TO VERY LARGE DETECTORS FOR ULTRAVIOLET ASTRONOMY

PROJECT:
High Performance Sealed Tube Cross Strip Photon Counting Sensors

SPONSORING ORGANIZATION:
Astrophysics Division's SAT Program

PROJECT LEAD:
Dr. Oswald Siegmund, UC Berkeley

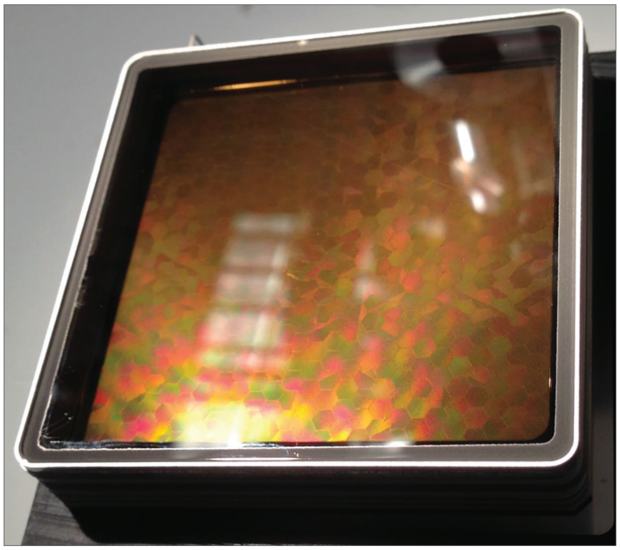
KEY POINTS:
These sensors represent an important enabling step in the development of large-area, high-resolution, very sensitive ultraviolet sensors for future-generation large space telescopes currently under study, such as LUVOIR and HabEx.

Future-generation large space telescopes under study at NASA will require very large, high-resolution, high-sensitivity, low-noise sensors capable of measuring ultraviolet through visible wavelengths. Armed with these advanced detectors, these missions would be capable of detecting and characterizing potentially habitable exoplanets. The Experimental Astrophysics Group at University of California Berkeley, in partnership with Photonis USA and INCOM Inc., is developing the pathway technology to realize these large area sensors.

Large area microchannel plate (MCP) detectors are part of the baseline plan for ultraviolet (UV) spectrographs on two of the large mission concepts being studied for inclusion in the National Academy of Sciences Astronomy and Astrophysics Decadal Survey (Astro2020). The Large Ultraviolet/Optical/Infrared Surveyor (LUVOIR) Ultraviolet Multi-Object Spectrograph (LUMOS) and the Habitable Exoplanet Observatory Ultraviolet Spectrograph (HabEx-UVS) will provide improvements in high contrast imaging and sensitivity, spectroscopy, astrometry, angular resolution and wavelength coverage. Both missions propose to employ arrays of large (100 mm and larger) high-performance MCP detectors.

With SAT funding, the Experimental Astrophysics Group at UC Berkeley is advancing the state of the art in MCP detector technology to meet the requirements of potential future large space missions and a variety of small (Explorer) and medium size (e.g., Cosmic Evolution Through UV Spectroscopy, or CETUS) missions. These on-orbit UV facilities would be able to probe the very limits of the universe. Principal Investigator (PI) Dr. Oswald Siegmund notes that, "The development of these large area

MCP detectors in the UV-Vis is an important enabling technology for the success of future missions like LUVOIR-LUMOS and HabEx-UVS."



▶ 50 mm sealed tube microchannel plate sensor.

MCP detectors with cross strip (XS) readouts have demonstrated potential to combine high spatial resolution (<20 µm) with photon-counting (noiseless) imaging in a robust, radiation-hard package that is scalable up to very large formats (>10 cm with 5,000 x 5,000 resolution elements). These detectors can also operate at room temperature with exceedingly low dark-background count rates and can even match the performance of curved optical focal planes.

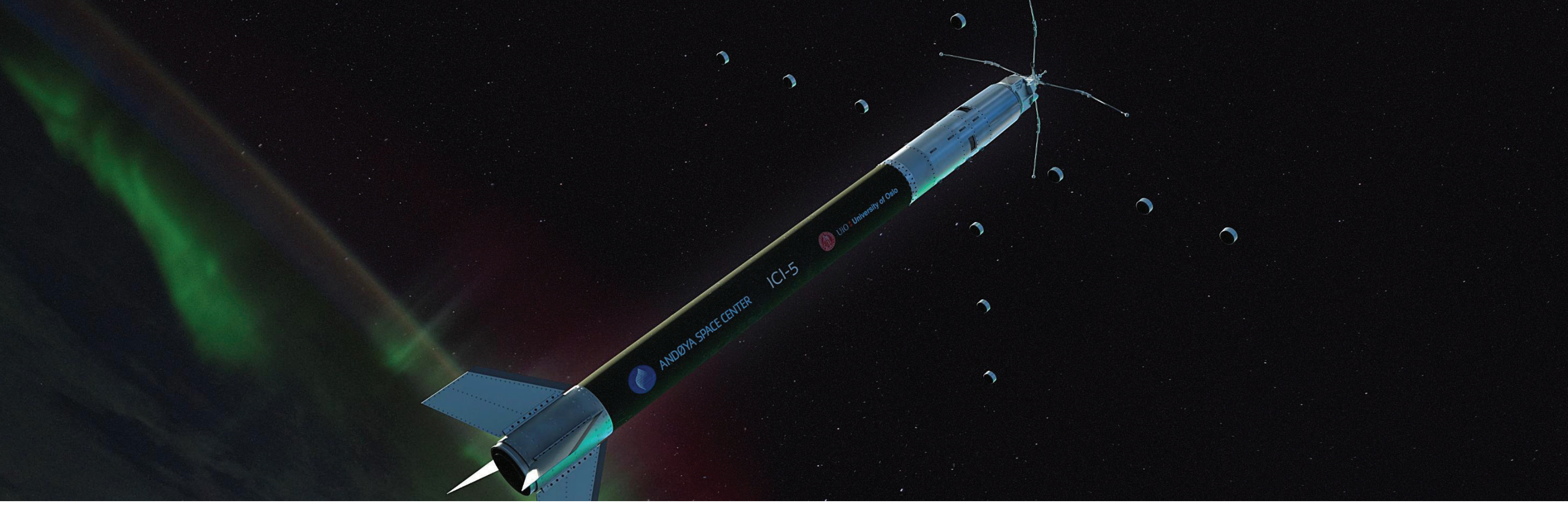
The objective of this SAT project is to exploit the developments in atomic layer deposited (ALD) MCPs, ultraviolet detection with high sensitivity photocathodes, and XS image readout techniques to provide a new generation of enhanced-performance, sealed-tube, photon-counting sensors that span the 115-nm to 400-nm wavelength range. The key to this effort is to demonstrate integration of XS readouts into sealed vacuum devices along with ALD MCPs. The final goal is to implement a robust, high-performance sensor that is advanced to Technology Readiness Level-6—i.e., demonstrated in a relevant environment.

Initial work in the first year of the project has successfully demonstrated the construction of XS ceramic anodes that are capable of very high-resolution imaging. Trials also show that they can be hermetically sealed to the final sensor enclosure. Preliminary ALD MCPs with 20-µm and 10-µm channel pore sizes have also been developed. These ALD MCPs show very low background noise characteristics and have already achieved the team's spatial resolution performance goals. Preliminary processing of ALD MCPs into sealed tube enclosures has been accomplished by our industry partner. The initial data demonstrates that the ALD MCPs suffer no loss of performance subsequent to this integration. Indeed, the post-processing tests with the sealed devices demonstrate better amplification statistics and a high degree of uniformity across the sensor active area. Photocathode deposition trials are also underway. The first tests show state-of-the-art sensitivity at short wavelengths. The trials also achieve photocathodes with a sharp long-wavelength cutoff that excludes red light, which would otherwise increase the effective background noise.

"The development of these large area MCP detectors in the UV-Vis is an important enabling technology for the success of future missions like LUVOIR-LUMOS and HabEx-UVS."

- PI, Dr. Oswald Siegmund

Further work in optimizing the ALD MCPs and photocathodes is currently underway as a precursor to integrating them into fully functional sealed devices. An upcoming major milestone is complete integration of an XS anode with MCPs and a photocathode in a hermetic sensor body. This Engineering Test Unit will enable us to assess the efficacy of the initial components and processing sequence to meet the sensor performance goals and to optimize the final sensor configuration.



Artist's rendition of the Investigation of Cusp Irregularities-5 (ICI-5) sounding rocket. (Image credit: Andøya Space Center/Trond Abrahamsen)

BIFOCAL ELECTRON SENSOR FLIGHT OF OPPORTUNITY ON THE INVESTIGATION OF CUSP IRREGULARITIES-5 MISSION

PROJECT:
ICI-5 Bifocal Flight Opportunity

SPONSORING ORGANIZATION:
Heliophysics Division's H-TIDeS Program

PROJECT LEAD:
Dr. Jasper Halekas, University of Iowa

KEY POINTS:
Developed by a team at the University of Iowa, the Bifocal sensor is a next-generation electron instrument with very high angular resolution. The Bifocal sensor will be demonstrated on the ICI-5 sounding rocket mission, and will provide measurements that enhance our understanding of ionospheric irregularities that can have societal impact.

Modern spacecraft missions require scientific instruments that provide high-quality data while utilizing minimal resources. To meet this need, a NASA-sponsored team designed the Bifocal electron sensor, a compact instrument that provides both routine survey measurements and targeted high-resolution electron observations. The Bifocal sensor will see its first demonstration flight on the upcoming Investigation of Cusp Irregularities-5 (ICI-5) mission from Norway, part of the multi-national "Grand Challenge Initiative – Cusp" program.

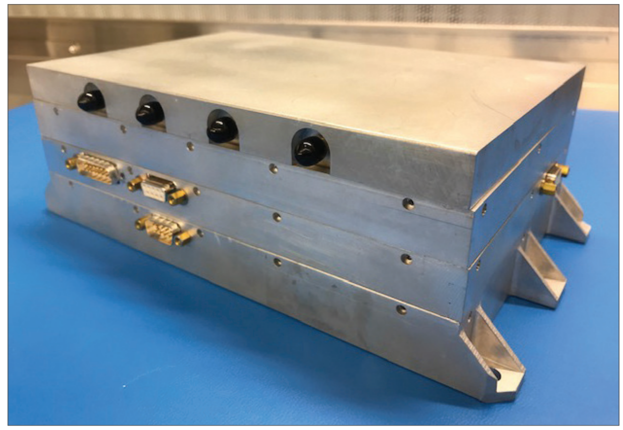
Over the past three years, a NASA-sponsored team led by Professor Jasper Halekas at the University of Iowa has developed a novel next-generation electron sensor that uses a combination of technologies to provide high angular resolution in two dimensions. The Bifocal sensor provides both coarse-resolution survey measurements of electrons from all directions and fine-resolution targeted measurements of electrons from any selected portion of the field of view. The Bifocal sensor accomplishes this feat by utilizing a pair of electrostatically controlled apertures (analogous to the two parts of the lenses of bifocal eyeglasses), paired with an imaging detector system.

To demonstrate the successful operation of the Bifocal sensor in a relevant environment and thereby increase the technology readiness level, a test flight is highly desirable. SMD's Heliophysics Division is therefore supporting a demonstration flight of the Bifocal sensor on the ICI-5 sounding rocket mission. ICI-5 will launch into the geomagnetic cusp in late 2019 from Norway, as part of the multi-national "Grand Challenge Initiative – Cusp" (GCI) program, which consists of eleven sounding rocket flights by nine teams from three countries.

The goal of the ICI-5 mission is to understand the structure and evolution of ionospheric irregularities – complex density structures that can form in the ionosphere – and the effects of soft electron precipitation on their formation. The geomagnetic cusp provides a unique location to conduct this investigation, since the magnetic field there provides a conduit for electrons to precipitate down onto the ionosphere and influence its structure. The Bifocal sensor will provide high-resolution electron measurements at a high temporal cadence in support of this scientific goal.

Understanding ionospheric irregularities is not only scientifically valuable, but has potential societal importance, since their presence can affect Global Positioning System (GPS)/Global Navigation Satellite System (GNSS) signal fidelity and satellite communications.

For this mission, the Iowa team integrated the prototype Bifocal sensor together with tailored electronics to produce the high voltages that control the Bifocal sensor apertures and interface to the ICI-5 digital processing and power systems. In 2019, the Bifocal sensor and the ICI-5/Bifocal electronics will be fully tested and qualified, integrated with the ICI-5 sounding rocket, and launched from Norway.



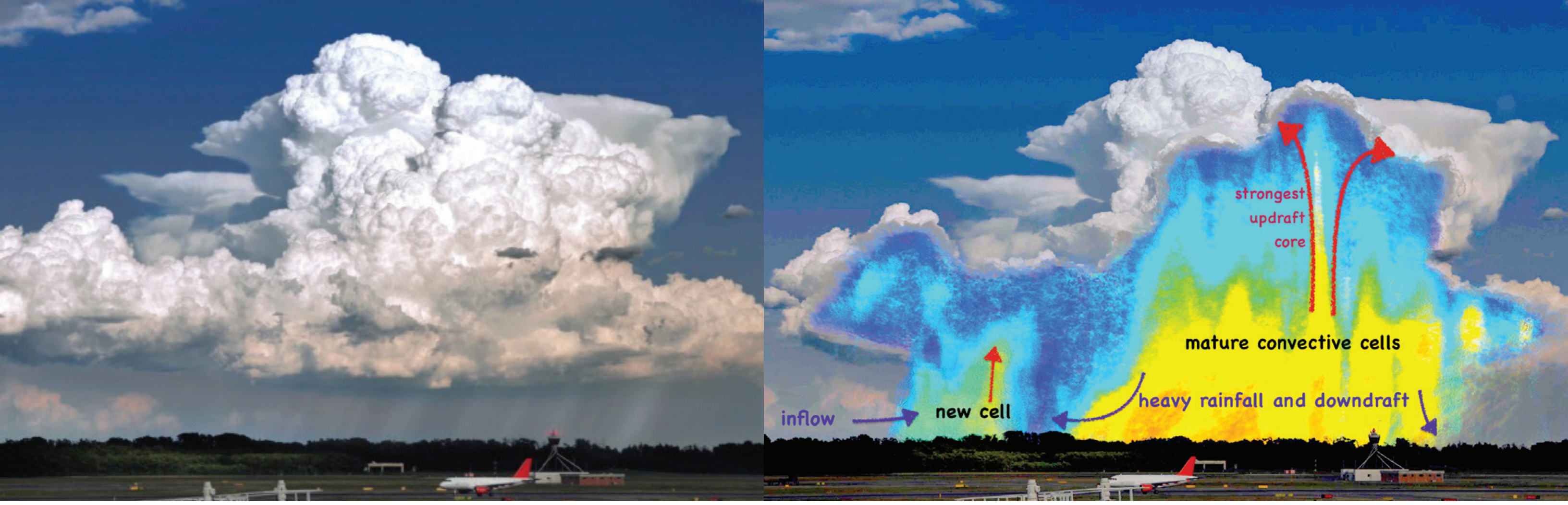
ICI-5/Bifocal Electronics Box.

The Bifocal electron sensor.

According to Prof. Halekas, "This flight of opportunity will not only help answer fundamental science questions about the ionosphere, but will demonstrate a new sensor appropriate for high-priority future NASA missions." The ICI-5 flight will result in a TRL 6 electron sensor that would meet the requirements of several upcoming heliophysics missions including the Geospace Dynamics Constellation (GDC), the Magnetosphere Energetics, Dynamics, and Ionospheric Coupling Investigation (MEDICI), and others.

"This flight of opportunity will not only help answer fundamental science questions about the ionosphere, but will demonstrate a new sensor appropriate for high-priority future NASA missions."

– PI, Prof. Halekas



The image on the right depicts the anatomy of the deep convection cloud on the left. The color contours of the cross section are observed hydrometeor sizes. (Image credit: NASA/GSFC Conceptual Image Lab)

SUPER CLOUD LIBRARY ENHANCES CLOUD PROCESS STUDIES

PROJECT:
Super Cloud Library

SPONSORING ORGANIZATION:
Earth Science Division's AIST Program

PROJECT LEAD:
Dr. Wei-Kuo Tao, NASA GSFC

KEY POINTS:
The Super Cloud Library—a big data analysis and visualization tool for Earth science applications—has been infused into the Data Analytics and Storage System (DASS) at the NASA Center for Climate Simulation and is producing results over twenty times faster than previously deployed manual processes.

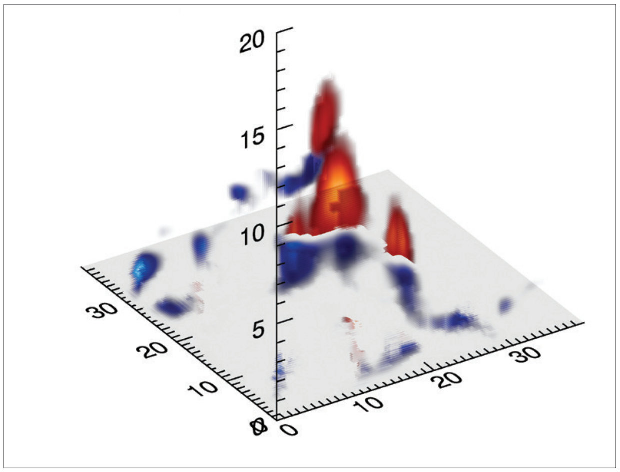
Today's high-performance computers consisting of hundreds of thousands of processors have enabled ultra-high-resolution, long-term Earth science simulations, such as those used to study cloud formation. The output files of these simulations can be huge—over 150 Terabytes. Not only are such large datasets hard to distribute, they are difficult to analyze with a desktop computer. A NASA team has developed a way for users to obtain adequate insight into these voluminous datasets without downloading them locally.

Researchers at Goddard Space Flight Center (GSFC) have developed the Super Cloud Library (SCL), a big data analysis and visualization tool for use with high-resolution cloud resolving models (CRMs). NASA recently infused the SCL into the Data Analytics and Storage System (DASS) at the NASA Center for Climate Simulation (NCCS) where it has enhanced CRM database management, distribution, visualization, subsetting, and evaluation.

"The Super Cloud Library implemented within the DASS has enabled climate researchers to analyze extremely large volumes of high-resolution model data without direct access to high-end computing."

- PI, Dr. Wei-Kuo Tao, NASA GSFC

The SCL architecture is built upon a Hadoop framework, which employs the Hadoop Distributed File System (HDFS)—a stable, distributed, scalable, and portable file system. Hadoop enables users to compute and visualize various standard/non-standard statistics. Within the Hadoop

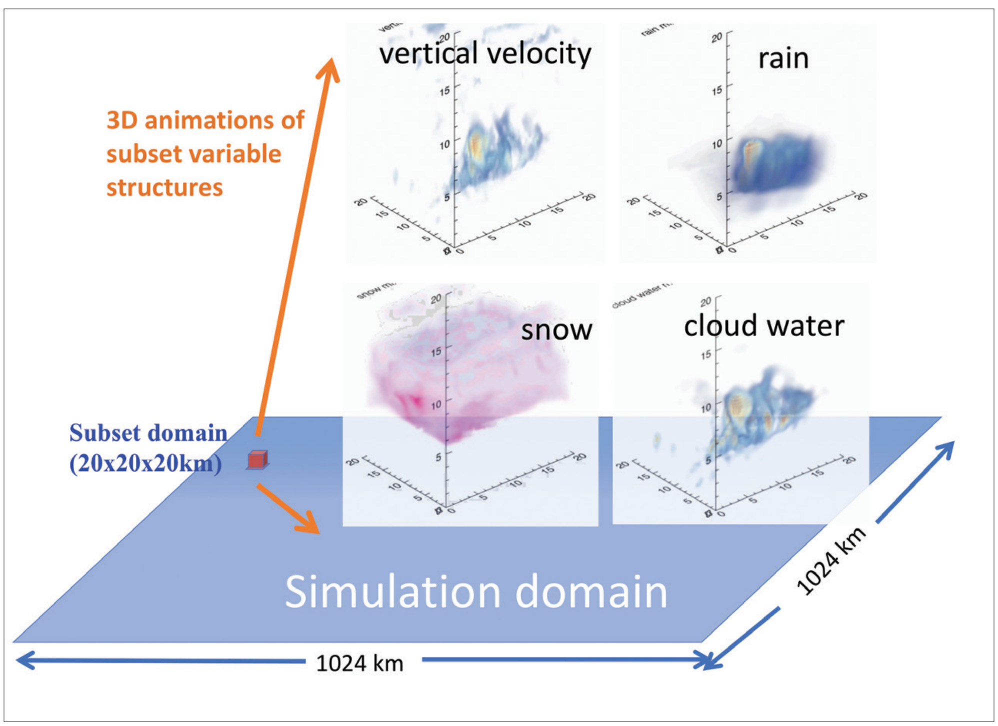


An example simulation showing a rain event. Updraft is shown in red and rain amount in blue.

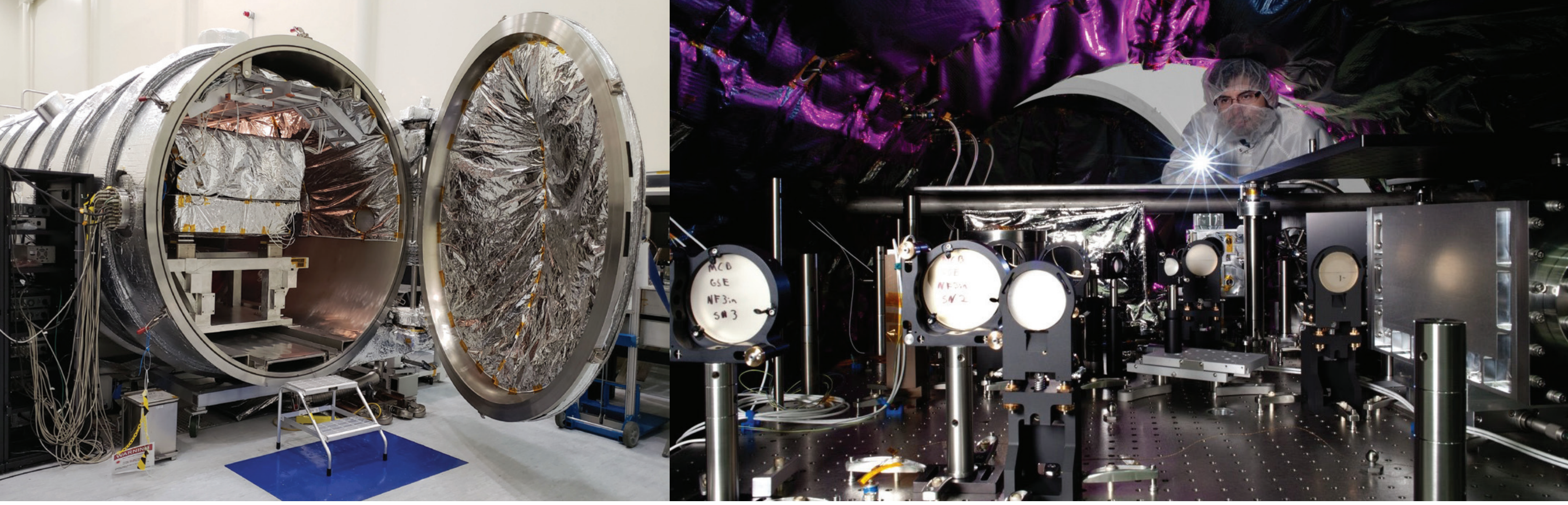
framework, a CRM's diagnostic capabilities are further enhanced with Spark (a big data processing tool), which accelerates the Hadoop MapReduce process by ~100 times.

The HDFS data model allows for transforming data from Network Common Data Form (NetCDF) to Comma Separated Values (CSV) format with indexes. Consequently, data can be stored in HDFS and straightforwardly processed by Hadoop-based tools for subsetting and diagnosis. HDFS's interface definition language (IDL) and Python tool permit users to visualize CRM-simulated cloud properties in two and three dimensions and diagnose HDFS-resident data. Moreover, HDFS's concurrent Hadoop reader is capable of increasing the speed of reading data from HDFS to be more than 20 times faster than sequential reading. Finally, the HDFS dynamic Hadoop reader can fetch Parallel File System-resident data and make them ready for MapReduce applications including subsetting and diagnosis.

The SCL was built on the NCCS Discover system, which directly stores various CRM simulations, including those produced by the NASA-Unified Weather Research and Forecasting (NU-WRF) model and Goddard Cumulus Ensemble (GCE) model. The team also developed a web portal for SCL to allow a user to subset, diagnose, visualize, save, and download the subset data. SCL allows users to conduct large-scale on-demand tasks automatically, without the need to download voluminous CRM datasets to a local computer. Therefore, the SCL makes CRM output more usable by the science community. SCL's Technology Readiness Level is level 5 (system prototype in an operational setting). As PI, Dr. Wei-Kuo Tao notes, "The Super Cloud Library implemented within the DASS has enabled climate researchers to analyze extremely large volumes of high-resolution model data without direct access to high-end computing."



Examples of dynamical subsetting of the convective core and associated rain, snow, and cloud water mixing ratio over a 3D box of 20 x 20 x 20 km (there are a total of two billion grid points in the whole 3D domain).



▶ Left: The Decadal Survey Testbed inside the vacuum chamber at the High Contrast Testbed Facility at the NASA Jet Propulsion Laboratory (JPL). Right: Manager of the testbed facility, Dr. Camilo Mejia Prada, looks into the vacuum chamber to view an ongoing coronagraph experiment.

THE DECADAL SURVEY TESTBED: DEMONSTRATING CORONAGRAPHS TO SEARCH FOR LIFE IN THE UNIVERSE

PROJECT:
Decadal Survey Testbed (DST)

SPONSORING ORGANIZATION:
Astrophysics Division's ExEP Office

PROJECT LEADS:
Drs. Keith Patterson & Byoung-Joon Seo, NASA JPL

KEY POINTS:
This advanced testbed enables the laboratory demonstration of coronagraph instruments capable of directly imaging Earth-like exoplanets and searching for signs of life from a future space observatory.

Earth-like planets orbiting other stars can be 10 billion times dimmer than their host star. To detect these planets and to search for spectroscopic signatures of life in their atmospheres, a space telescope must be used, and the light from the host star must be blocked so the planet comes into view. For the first time, a next-generation testbed is now available for demonstrating coronagraph instruments capable of imaging these planets.

The Astrophysics Division's Exoplanet Exploration Program (ExEP) Office has commissioned a testbed to demonstrate new coronagraph technology for imaging nearby Earth-like planets with a future space telescope. The Decadal Survey Testbed (DST) is a new optical bench built from the ground up with extreme thermal and vibrational stability in a vacuum chamber with a coronagraph instrument.

The search for life in the universe is one of NASA's loftiest goals. Thanks in part to NASA's Kepler mission, we know that planets orbit nearly every star. Determining evidence for life on the abundant planets in the galaxy will involve measuring visible-band and near-infrared spectra of the planets to look for the presence of biosignature gases like oxygen, carbon dioxide, water, and possibly methane. NASA is now conceiving future space missions capable of spectral characterization of distant planets. These include LUVOIR, Habitable Exoplanet Observatory (HabEx), and Origins concept studies commissioned by NASA.

An Earth-like planet is 10 billion times dimmer than a Sun-like star, and the planet and star are very close to each other in angular distance on the sky. An essential step in directly measuring a distant planet is to perform starlight suppression, reducing the light from the host star enough that the planet can come into view. One technique to perform this suppression uses a coronagraph instrument on a space telescope. This instrument uses a series of intricate masks to block light from the star while allowing light from the orbiting planet to pass through to a camera. While coronagraphs have been in operation since the 1930s for observing our Sun and have been used for astronomy on the Hubble Space Telescope, an advanced stellar coronagraph capable of studying a distant Earth-like planet has not yet been built.

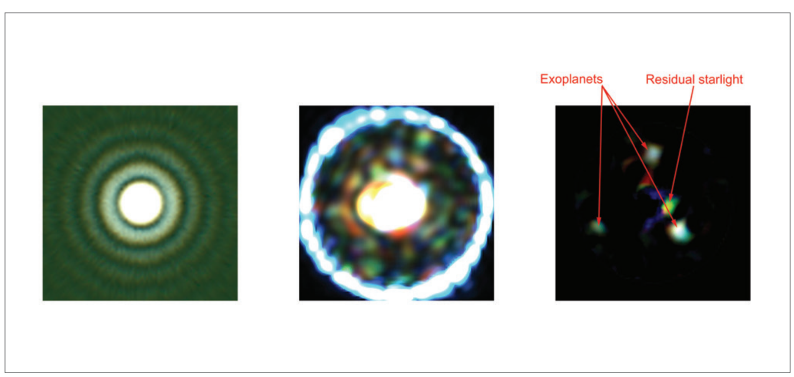
Achieving a factor of 10 billion in contrast is a huge challenge, mainly because any imperfection in the optics can diffract light around the masks. Future space telescopes could have segment gaps and secondary mirror support structures that also diffract the incoming starlight in a way that is challenging for a coronagraph to handle. Vibrations on a spacecraft and heating and cooling of the space telescope can introduce disturbances in the optical path that a coronagraph must handle and compensate dynamically. Most of this correction is done using deformable mirrors: flat, flexible mirrors that have a grid of tiny pistons behind the reflective surface that can reshape it to a small fraction of the wavelength of light, to the picometer scale.

The Coronagraph Instrument (CGI) technology demonstrator on NASA's Wide Field Infrared Survey Telescope (WFIRST), scheduled for the late 2020s, is making essential progress in maturing exoplanet imaging technology for space, but CGI is not designed to achieve the factor of 10 billion improvement in contrast needed to find Earth-like planets. Beyond CGI, coronagraph designers have developed advanced masking techniques and deformable mirror technology that, in principle, can achieve the factor of 10 billion in contrast. But NASA needs a way to demonstrate that this technology works in a space-like environment.

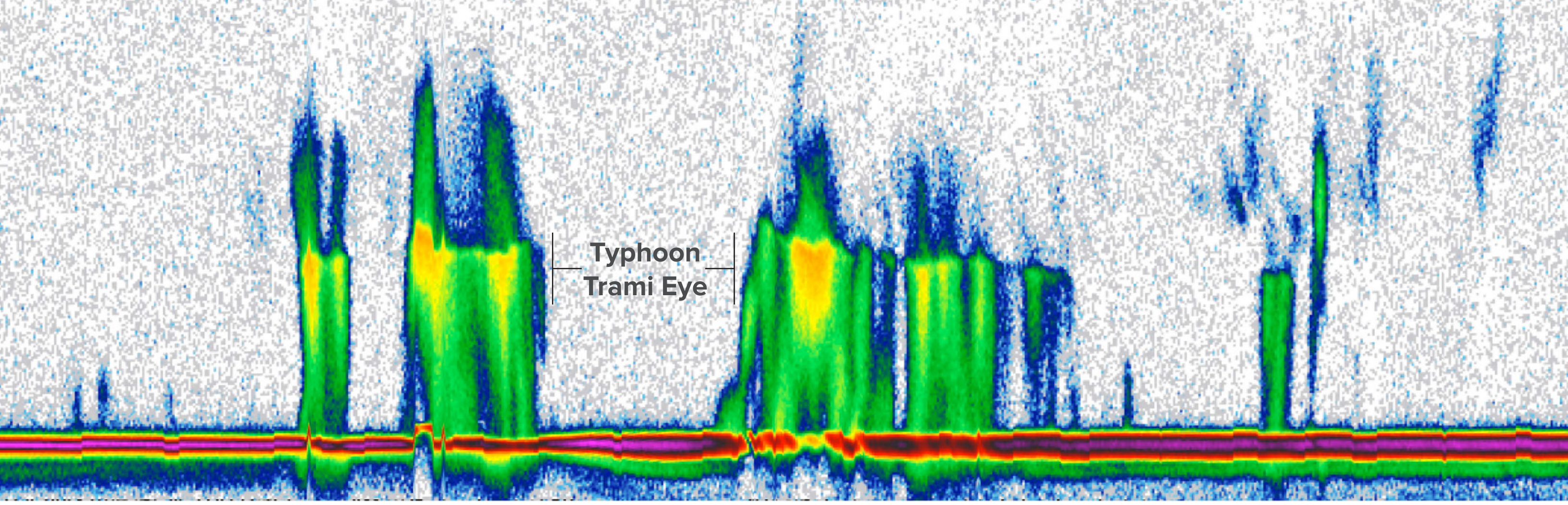
The DST meets this need with a new advanced testbed that eliminates disturbances from the laboratory and local environment as much as possible. At its foundation, the DST consists of a carbon-fiber optical table that is highly stable to thermal fluctuations and includes active temperature control on all optics. The bench is mounted on vacuum-compatible vibration isolators to reduce sensitivity to seismic and laboratory vibrations. Every mirror in the system is designed to be thermally stable, and a fast tip/tilt steering mirror will actively suppress residual mechanical vibrations. Two deformable mirrors allow the optical imperfections to be corrected. The entire testbed is inserted into a 12-m long vacuum chamber at JPL, eliminating effects of the atmosphere and better simulating the space environment.

The team at JPL assembled and aligned the DST, finally inserting the bench into the vacuum chamber in the summer of 2018. The initial commissioning tests include demonstrating the performance of a Lyot coronagraph. As of February 2019, the team has shown that the testbed is sensitive enough to detect a planet 1×10^{-10} times as bright as the star at high significance. In practice, the choice of observation strategies and data post-processing will allow for further improvement of this detection limit. Later in 2019 and 2020, the team will add additional complexity by simulating the effects of a segmented primary mirror and aim for the same extreme starlight suppression.

The DST is available to investigators funded via NASA's SAT program to demonstrate new coronagraph ideas. As the HabEx and LUVOIR teams develop scientific and technical plans for future direct imaging missions, this new testbed will help NASA advance technology capable of discovering life around distant planets.



▶ False-color images of a star and simulated exoplanets fed by actual experiment data. Left: the host star as viewed without a coronagraph where the exoplanets are hidden by the starlight's diffraction rings. Center: a testbed image around a billion times fainter after almost all of the starlight is removed by the coronagraph instrument. Right: the image after post-processing removal of residual starlight that reveals three distinct exoplanets originally hidden in the glare of their star.



▶ Precipitation profile of Typhoon Trami generated by RainCube on September 28, 2018.

RAINCUBE DEMONSTRATES MINIATURE RADAR TECHNOLOGY TO MEASURE STORMS

PROJECT:
RainCube (Radar in a CubeSat)

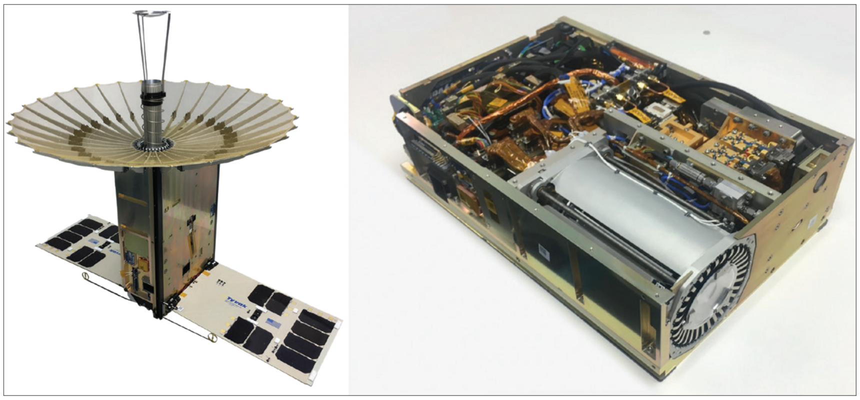
SPONSORING ORGANIZATION:
Earth Science Division's InVEST Program

PROJECT LEAD:
Dr. Eva Peral, NASA JPL

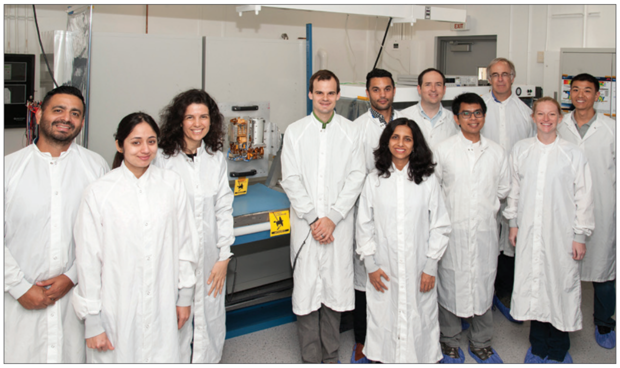
KEY POINTS:
RainCube successfully demonstrated Ka-band precipitation radar technology on a low-cost, quick-turnaround platform. This new technology will enable constellations of small spacecraft that can track storms and provide data about how the storms evolve in short time scales—capabilities that are needed to improve numerical weather and climate models.

Accurate prediction of severe storms yields numerous societal benefits—from predicting when and where disaster relief may be required, to helping you decide whether to take an umbrella when you leave your house. But to improve these predictions, scientists need a way to measure the movement of water and air in thunderstorms globally. RainCube has demonstrated a technology that will enable such measurements to be collected on a global scale in a cost-effective manner.

Developed at the NASA Jet Propulsion Laboratory (JPL), RainCube has demonstrated a new architecture for miniaturized Ka-band precipitation radars. Following a successful deployment from the International Space Station in July 2018, the RainCube radar was turned on in late August, and successfully acquired vertical range profiling measurements of



▶ RainCube CubeSat flight hardware (deployed on left, stowed on right). Tyvak, Inc was responsible for the bus delivery and flight integration and performed mission operations. NASA JPL developed the radar instrument and was responsible for system engineering and project management. (Credit: NASA JPL)



The RainCube team in the lab at NASA JPL.

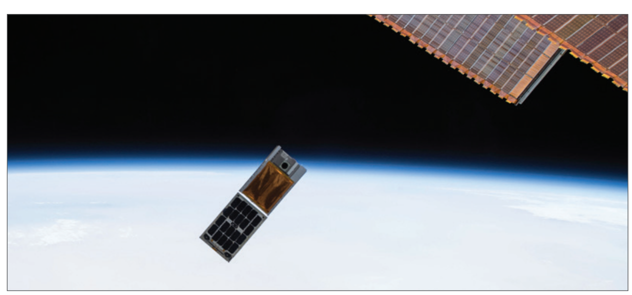
precipitation and land surface at a nadir-pointing configuration. Since then, it has continued to acquire additional measurements, including the vertical precipitation profile of Typhoon Trami on September 28, 2018, shown on the previous page.

RainCube uses Ka-band radar to "see" into storms. The satellite sends a radar signal towards the storm being observed, and receives a signal back as the radar bounces off raindrops in the storm. This capability provides a picture of the activity inside the storm such that scientists can learn about the processes that make the storm grow or decay.

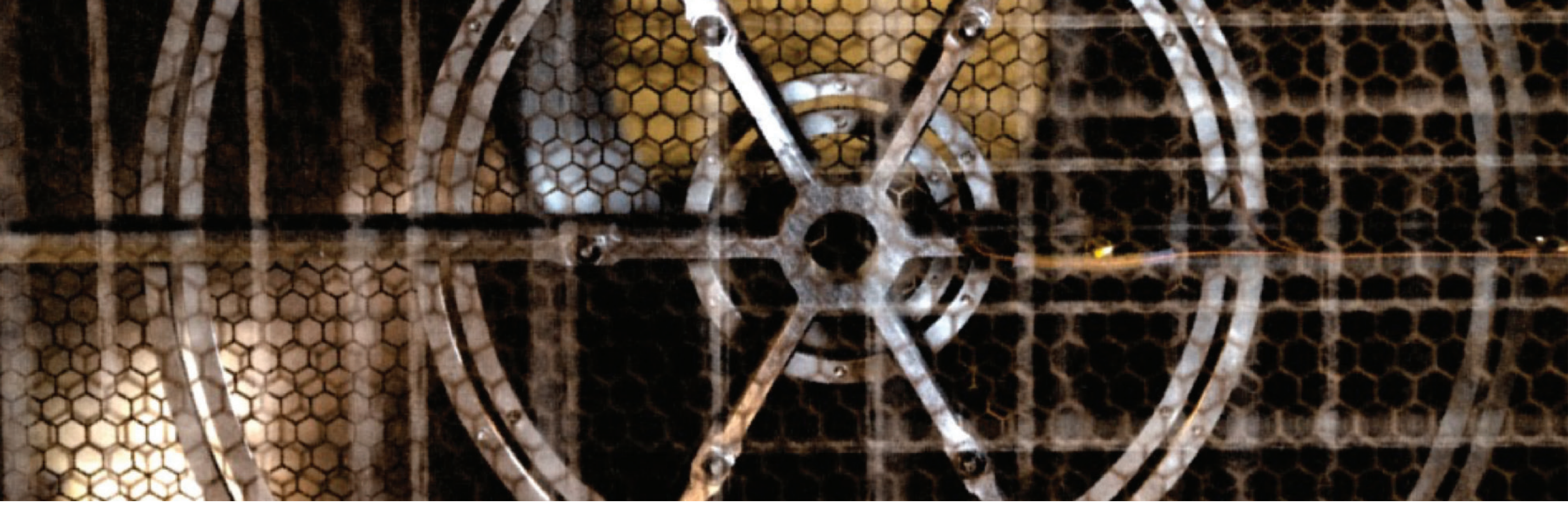
A network of ground-based weather radars provides much of the information currently used to produce weather forecasts. However, these systems have several limitations that prevent them from providing a global view of storm activity: only developed countries are capable of supporting such networks, measurements over oceans are largely unattainable, and many mountain ranges present significant challenges to these ground-based measurement systems. Weather satellites provide a global view, but can only capture images of the tops of the storms; they do not provide much of the information that is needed to understand what is happening inside the storms. A couple of spacecraft with downward-looking cloud or precipitation radars have enabled improved understanding of the structure and global distribution of storms, but these missions are usually expensive and thus it is cost-prohibitive to launch a constellation that would enable continuous global coverage.

As PI Dr. Eva Peral notes, "RainCube introduces a new paradigm to observe weather processes by enabling a constellation of precipitation-profiling radars, which would revolutionize climate science and weather forecasting." The RainCube radar takes measurements in a geometry similar to other existing spaceborne radars, but its novel architecture reduces power consumption, mass, volume, and the number of components by more than an order of magnitude with respect to those instruments. Thus, the RainCube architecture is compatible with the volume, mass, and power constraints of small satellites, significantly reducing the manufacturing cost. The RainCube mission ultimately demonstrates the potential for an entirely new and different way of observing Earth with a constellation of low-cost small radars. A constellation of "RainCube-like" spacecraft would provide the spatial and temporal coverage and sampling that are needed to improve our understanding of Earth's water cycle and eventually advance the numerical models that are used for weather forecasting, enabling more accurate prediction of rain, snow, sleet, and hail.

> **"RainCube introduces a new paradigm to observe weather processes by enabling a constellation of precipitation-profiling radars, which would revolutionize climate science and weather forecasting."**
>
> **- Dr. Eva Peral, NASA JPL**



RainCube (left) and another CubeSat called HaloSat (right) following ISS deployment.



The Hyperdust prototype instrument's ion optics. (Image credit: Tibor Balint)

SURVEYING THE BUILDING BLOCKS OF THE SOLAR SYSTEM

PROJECT:
High-Performance In Situ Dust Analyzer (Hyperdust)

SPONSORING ORGANIZATION:
Planetary Science Division's MatISSE Program

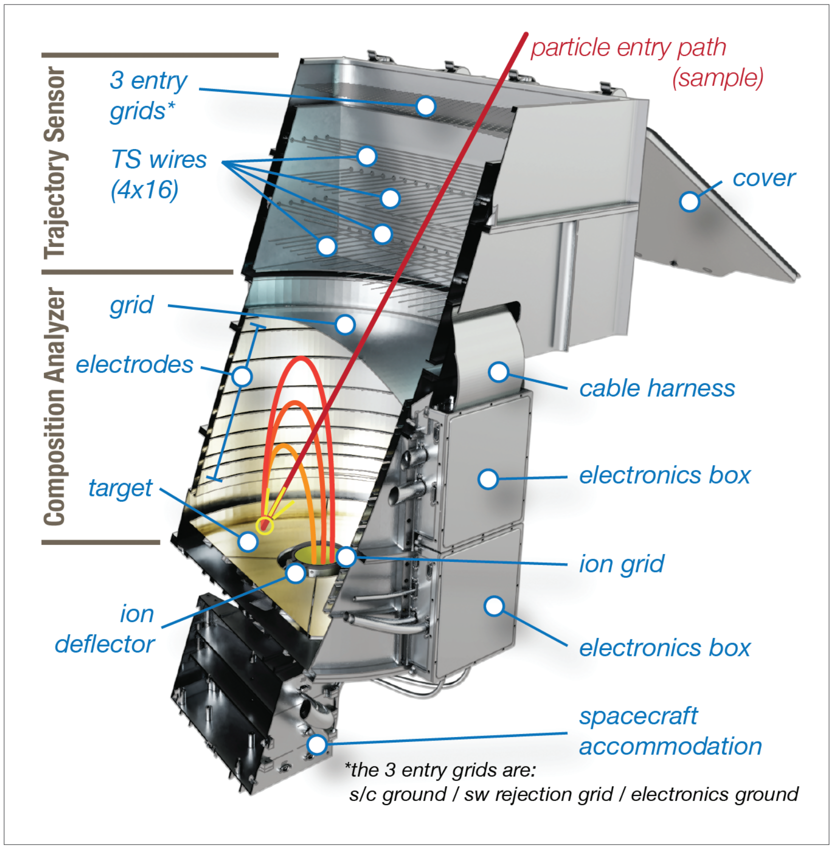
PROJECT LEAD:
Dr. Zoltan Sternovsky, University of Colorado

KEY POINTS:
Hyperdust's unique ion optics design combines the ability to provide high-performance composition measurements with the aperture that is needed to detect a statistically significant number of particles in space over a standard mission duration of a few years.

The history of the formation and evolution of the Solar System is encoded in the compositional diversity of its small bodies, including comets and asteroids, and the solid material that was the source of it all: interstellar dust. But there are simply too many small bodies to be visited and investigated individually. Instead, what if scientists could survey the tiny particles (microsamples) that originate from these bodies and are delivered near Earth's orbit by dynamic processes?

The High-Performance In Situ Dust Analyzer (Hyperdust) Project is developing a highly capable instrument to measure the compositional diversity of many thousands of solid particles in space. The Composition Analyzer part of this instrument is now in development for deployment on NASA's Interstellar Mapping and Acceleration Probe (IMAP) mission to be launched in 2024. Over the past four years, the Hyperdust Project has been maturing a novel instrument concept that will provide the capability of analyzing the composition of micron- and submicron-sized cosmic dust particles with higher resolution and sensitivity than ever before. The National Research Council's 2013 Planetary Science Decadal Survey notes that, "There are too many asteroids, comets and KBOs [Kuiper belt objects] to explore individually by spacecraft." Over the past 30+ years, in situ composition measurements have been obtained only for a handful of asteroids and comets. The Hyperdust instrument offers a paradigm shift, from an approach limited to observing a few bodies individually, to one surveying the entire solar system and beyond.

Hyperdust is a complex instrument that measures the velocity vector and composition of each cosmic particle encountered in space. The former measurements are accomplished by the Trajectory Sensor, which consists of an array of wire electrodes that sense the particles when they enter through

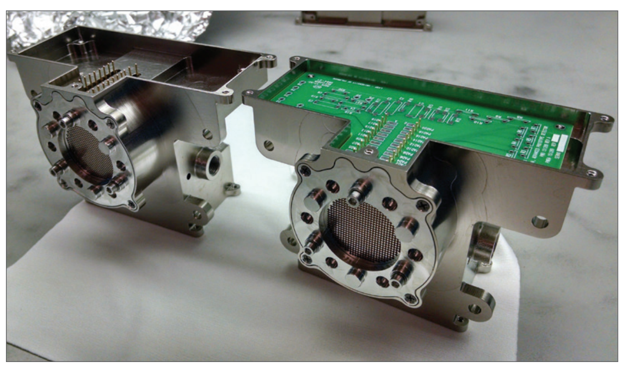


▶ The schematics of the full Hyperdust instrument. The Hyperdust Project team developed many of the key technologies enabling the instrument's unique capabilities. (Image credit: Tibor Balint)

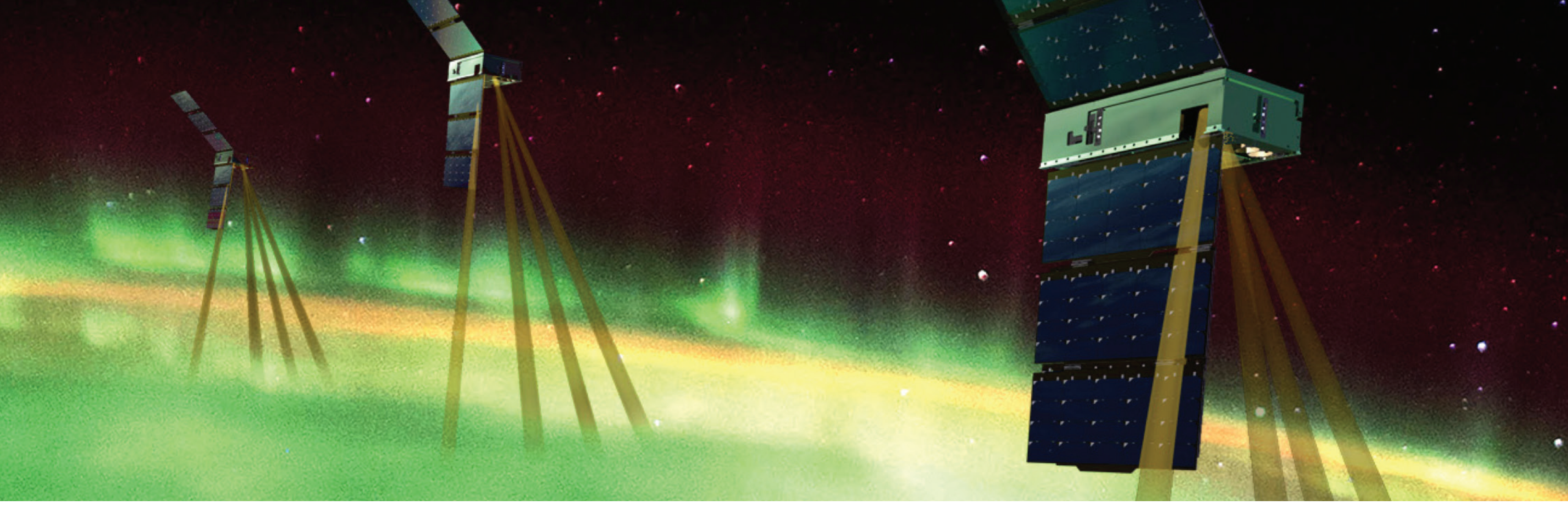
The full Hyperdust instrument is approximately 70 cm tall and has a disk-shaped impact collection surface that is 40 cm in diameter. Such large size is needed to collect a statistically significant number of particles and their composition information. The Composition Analyzer part of the instrument has been selected to fly on the IMAP mission—the fifth mission selected in NASA's Solar Terrestrial Probes program. The goal of the IMAP-bound instrument is to map out the composition of interstellar particles traversing through the solar system and link their composition to the characteristics and physical processes of the interstellar medium.

the aperture. The velocity information is used to identify the origin of each particle based on its orbit around the Sun. The Composition Analyzer then measures the composition of ions that are generated by the high-speed impact of the dust particle on a clean metal surface. This information reveals the elemental and chemical composition of the impacting dust. The Hyperdust project team developed key elements of this measurement capability, namely the sensitive electronics needed to detect the particle in the Trajectory Sensor, the refined ion optics, and the ion detector.

Besides detecting and analyzing cosmic dust in interplanetary space, the technology advanced during development of the Hyperdust instrument is also supporting exploration of icy worlds and their habitability. For example, NASA is developing the SUrface Dust Analyzer (SUDA) instrument for the Europa Clipper mission. SUDA carries an ion detector that is based on that developed for Hyperdust. The SUDA instrument will analyze the icy particles originating from the surface of the Jovian moon Europa, and identify the chemicals embedded in the ice, both organic and inorganic.



▶ Two copies of the SUDA ion detector prototype. The SUDA detector is built on the Hyperdust technology development. (Image credit: LASP/CU)



Artist's depiction of a series of small satellites orbiting Earth, each bearing the Microwave Electrojet Magnetogram (MEM) sensor to image ionospheric currents.

NEW COMPACT REMOTE SENSOR TO IMAGE IONOSPHERIC CURRENT'S SPATIAL STRUCTURE FROM SPACE

PROJECT:
The Microwave Electrojet Magnetogram (MEM)

SPONSORING ORGANIZATION:
Heliophysics Division's H-TIDeS Program

PROJECT LEAD:
Dr. Jeng-Hwa Yee, Johns Hopkins Applied Physics Laboratory

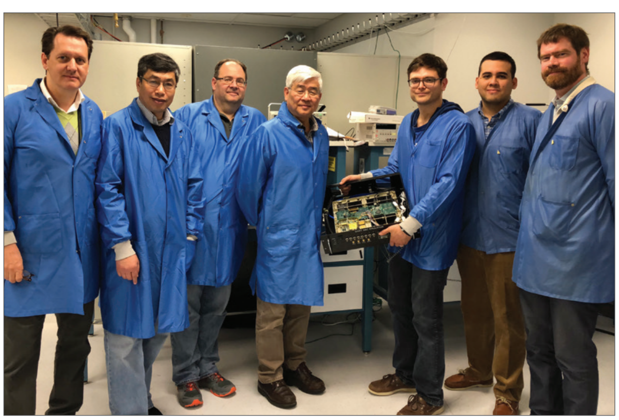
KEY POINTS:
The low SWaP MEM sensor enables cost-effective implementation of future high-impact ionospheric current investigations on resource-limited missions, including CubeSat constellations.

Understanding the interaction and coupling processes within Earth's atmosphere, ionosphere, and magnetosphere system is one of the key scientific challenges identified in the *Decadal Strategy for Solar and Space Physics (Heliophysics)* in 2012. Observations of ionospheric electrojet currents flowing around 105-km altitude are crucial to this endeavor but have been thus far unobtainable. These currents are part of a vast current system flowing between the magnetosphere and the ionosphere and the lack of measurements have left many fundamental questions unanswered despite several decades of research. NASA is currently developing a new remote sensing instrument to cost-effectively provide these critically needed measurements.

Over the past year, NASA's Microwave Electrojet Magnetogram (MEM) project has been maturing a novel low size, weight, and power (SWaP) array receiver capable of remotely imaging the ionospheric current structure from an orbital platform. Each element of this MEM sensor spectrally resolves the three Zeeman-split O_2 thermal lines at 118 GHz and provides measurements of the current-induced magnetic field globally at multiple locations simultaneously under all solar and atmospheric illumination conditions. Traditionally, these ionospheric current strengths have been inferred from magnetic field variations detected by ground-based magnetometers below the currents and spaceborne magnetometers high above the currents. The measurements from these methods, however, are either spatially sparse (from the ground) or smeared with degraded spatial resolution (from space). The groundbreaking MEM measurements will overcome these limitations and provide the first-ever, simultaneous magnetic field measurements at multiple locations and times near altitudes of ~105 km from a single spacecraft.

MEM is a modern microwave receiver system that consists of multiple heterodyne full-Stokes spectro-polarimeters operating at ambient temperature. The front-end of each polarimeter collects the incoming 118 GHz signal and non-linearly mixes it with the signal generated by a reference local oscillator (LO) that is set at a nearby frequency. The mixed output at the different frequencies conveys the amplitude and phase of the original higher frequency 118 GHz signal, but at a lower, more easily processed, carrier frequency. The receiver front-end is technologically mature and can be built compactly—the size of a human thumb—and is thus easily accommodable on CubeSat or SmallSat platforms. A critical challenge of the multi-element MEM concept is the power consumption and the size of multiple spectrometers in the receiver back-end.

The MEM project team, led by Dr. Jeng-Hwa Yee at the Johns Hopkins University, Applied Physics Laboratory (APL), is currently developing a multi-mission compact and low-power Baseband Spectrometer Module (BSM). The architecture of this BSM is scalable to support a varying number and type of sensing elements and thus a variety of mission concepts. The hardware realization is small, low-power and radiation tolerant. The BSM design is based on a flight technology development program at APL, the CoreSat Single Board Computer (SBC). The CoreSat SBC is a 4” by 6” card that can support both general command and data handling, as well as specialized digital signal processing applications.



▶ The MEM team from left to right: Dr. Jesper Gjerloev, Dr. Dong Wu, Dr. Mark Martin, Dr. Jeng-Hwa Yee, Jeff Boye, Christian Campo and Dr. Norm Adams. Jeff is holding a test chassis that contains a CoreSat Single-Board Computer (SBC). The chassis provides convenient electrical connections for configuration and test.

▶ MEM compact and low-power Baseband Spectrometer Module (BSM) is designed based on an APL proprietary prototype Single Board Computer (SBC) card shown here with part labels obfuscated.

The MEM BSM utilizes a modular and scalable architecture to simplify the CoreSat SBC. Unnecessary components are either removed or reduced in number, yielding a smaller and more power-efficient BSM card that can be mated to a carrier card designed for any specific mission.

MEM has a flexible design so that the number of elements, exact look angles, and combination of polarizations can be tailored to meet the requirements of the desired missions. According to Dr. Yee, “A single spacecraft ionospheric current mission carrying a four-element MEM sensor would be equivalent to flying four spacecraft equipped with low-noise magnetometers and its measurements would not be affected by the distance to the currents.” While the MEM receiver front-end is technologically mature, the ongoing receiver back-end—the BSM development effort—will result in a TRL 6 technology for deployment in NASA’s future heliophysics missions. To further advance the MEM’s TRL, the project is building a BSM prototype and verifying its performance and power consumption.

“A single spacecraft ionospheric current mission with a four-element MEM sensor onboard would be equivalent to flying four spacecraft equipped with low-noise magnetometers...”

- Dr. Jeng-Hwa Yee

NEW LASER TRANSMITTER TO ENABLE INTERNATIONAL GRAVITATIONAL WAVE OBSERVATORY

PROJECT:
Laser Transmitter for the Laser Interferometer Space Antenna (LISA) Mission

SPONSORING ORGANIZATION:
Astrophysics Division's PCOS Program

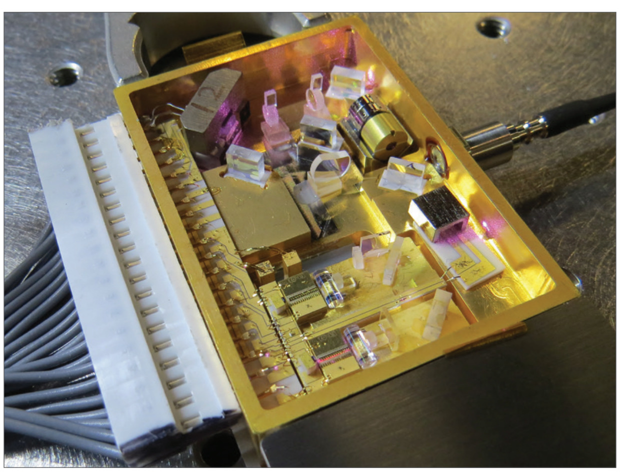
PROJECT LEAD:
Dr. Anthony Yu, GSFC

KEY POINTS:
A highly stable and robust laser design is a key subsystem required for the LISA observatory. By leveraging lessons learned from previous missions and the latest technologies in photonics packaging and reliability engineering, NASA is developing a master oscillator power amplifier laser transmitter to meet the challenging LISA requirements.

What happens when two black holes that are each a million times bigger than our Sun collide? NASA and the European Space Agency are jointly developing the Laser Interferometer Space Antenna (LISA) to tell us more about the gravitational waves produced by such astronomical phenomena.

LISA will consist of three spacecraft flying in a constellation, each separated by 2.5 million km. Gravitational waves are incredibly elusive; to detect them scientists will need to track changes in the separation of the three LISA spacecraft with amazing precision—just a few picometers, a dimension smaller than the size of a hydrogen atom. A team at NASA GSFC is developing a new laser system to meet this challenge.

The laser system is one of the most important subsystems of the LISA measurement system, since it will provide the light used to make the sensitive interferometric distance measurement between the spacecraft. Over the past four years, a team at NASA GSFC has been developing a highly stable and robust laser system for the LISA mission. NASA's baseline architecture for the LISA laser is a master oscillator power amplifier (MOPA) laser transmitter. As the name suggests, the MOPA architecture entails two major subsystems: (1) the master oscillator (MO), a lower power laser that meets majority of the laser requirements except power; and (2) the power amplifier (PA), which boosts the low output power of the MO to the required power without imparting additional noise.

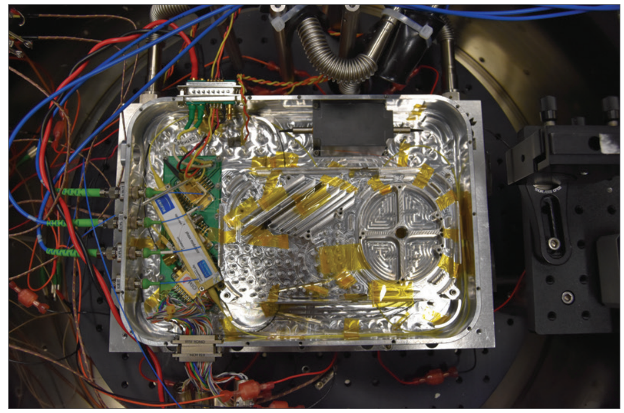


▶ Final product of the Phase 1 master oscillator package.

The NASA team has designed the LISA laser system to satisfy the familiar mass, power, and radiation hardness requirements for space-based lasers. But LISA also has some unique requirements arising from its role in the interferometric measurement system. It must have exquisite stability in both wavelength (which requires active stabilization using a high finesse optical cavity) and intensity (which requires active stabilization for long-term drifts and quantum-limited performance over short time scales). In addition, the laser must be robust enough to survive 16 years of operation, from early ground testing through the extended mission phase. The GSFC design goal is to minimize the MO size, weight, and power but have enough optical power to properly seed a single-stage power amplifier. The design also minimizes the number of components in the laser, but allows proper derating and built-in redundancy to meet mission requirements. To achieve these goals, the GSFC team designed a custom micro non-planar ring oscillator (mNPRO) laser.

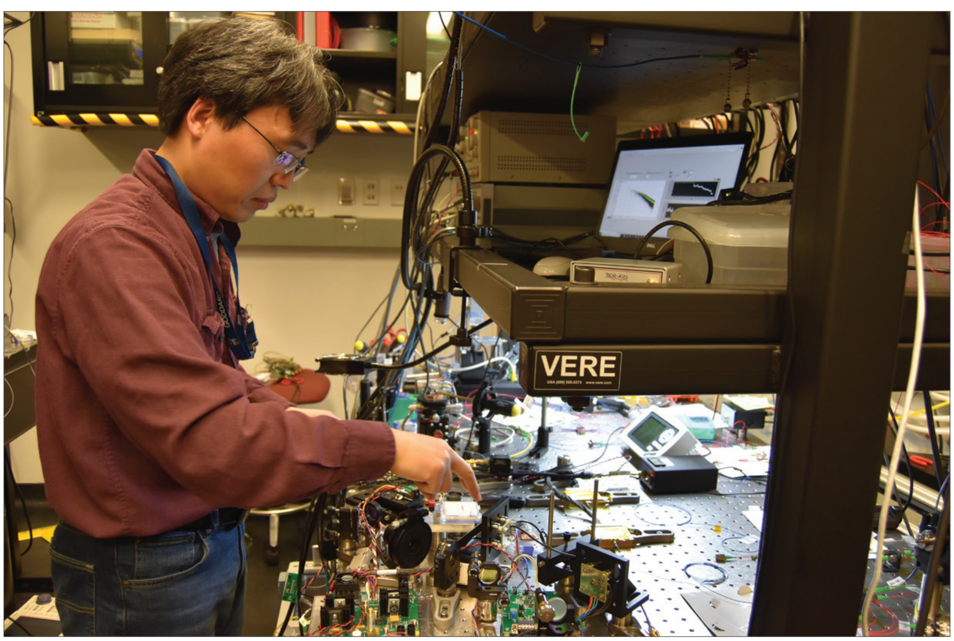
The unique LISA requirements make evaluation of the laser performance challenging. To enable testing of these lasers, the GSFC team built a laser characterization infrastructure that differs from those found in industry, other Government labs, or academia. These in situ test capabilities provide important advantages including time savings, cost savings, and improved ability to meet compliance requirements.

Recently, the team completed assembly of the first-generation mNPRO MO laser, which leverages the latest telecommunications packaging techniques for assembling electro-optics components such as the laser diodes, laser crystals, thermoelectric coolers, etc. The team also initiated the next-generation design, with a target date of completing laboratory testing by the end of summer 2019. In addition, team members built and successfully demonstrated a PA that meets the LISA functional requirements and are preparing it for space flight qualification in a year's time.

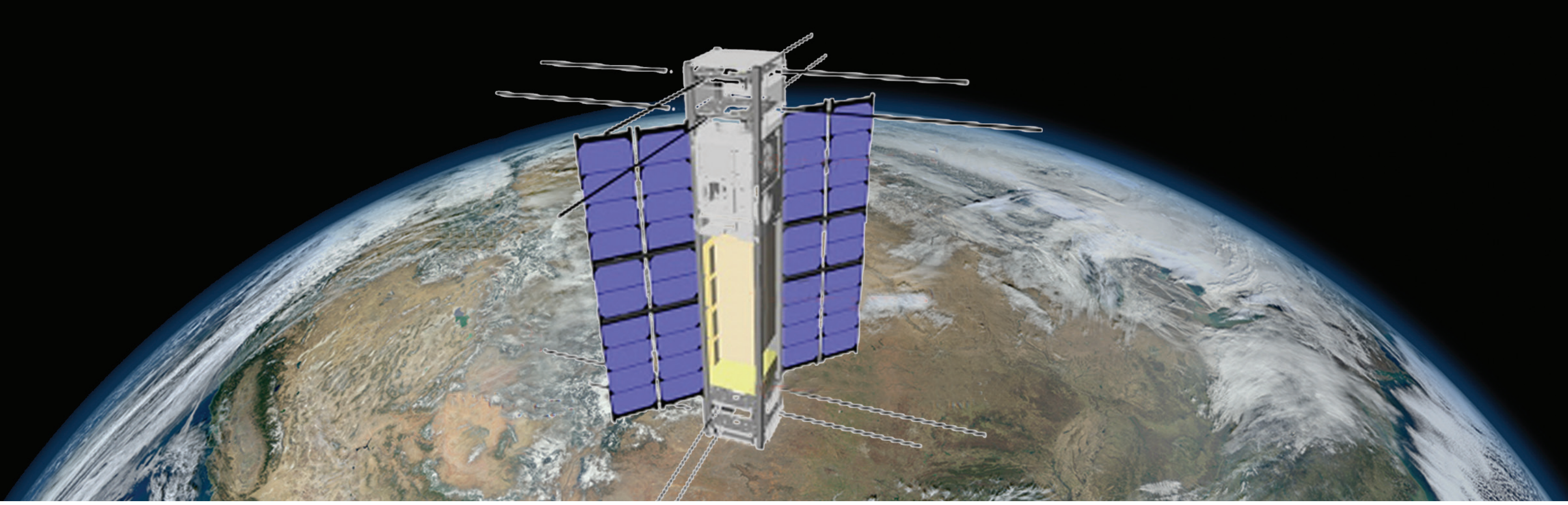


▶ GSFC in-house power amplifier assembly that meets the LISA requirements.

In the next two years, the GSFC laser team will continue work on the U.S. laser system for LISA, including: (1) packaging and full performance testing of the new mNPRO design, (2) PA architecture evaluation and selection, (3) reliability testing of the laser system and components to show compliance with the 16-year LISA lifetime requirement, and (4) demonstration of noise and locking performance when combined with other subsystems. Delivery of a form, fit, and functional laser to the European Space Agency (ESA) for test is scheduled for early 2020 and the team plans to provide a fully space-qualified MOPA laser by mid-2021.



▶ Dr. Kenji Numata (GSFC) testing the mNPRO modules.



Artist's rendition of the SigNals of Opportunity: P-band Investigation (SNoOPI).

CUBESAT MISSION TO DEMONSTRATE INNOVATIVE METHOD FOR MAPPING SOIL MOISTURE AND SNOW FROM SPACE

PROJECT:
Signals of Opportunity Airborne Demonstrator (SoOp-AD) and SigNals of Opportunity: P-band Investigation (SNoOPI)

SPONSORING ORGANIZATION:
Earth Science Division's IIP and InVEST Programs

PROJECT LEAD:
Dr. James Garrison, Purdue University

KEY POINTS:
The SoOP-AD project successfully demonstrated, from aircraft, a new instrument prototype for remote sensing of soil moisture. The SNoOPI project will continue this development by demonstrating this technology from space on a CubeSat platform. Success with SNoOPI will show that this technique is viable in space and would be available for use on future satellite missions.

Space-based methods to measure soil moisture on Earth typically entail either sensing the extremely weak emission of microwaves from water in the soil using an instrument call a radiometer or using a radar, which transmits a signal toward Earth, and then receives the signal after it reflects from the soil. Using current technology, neither approach can sense changes in the soil moisture deeper than about five centimeters below the surface.

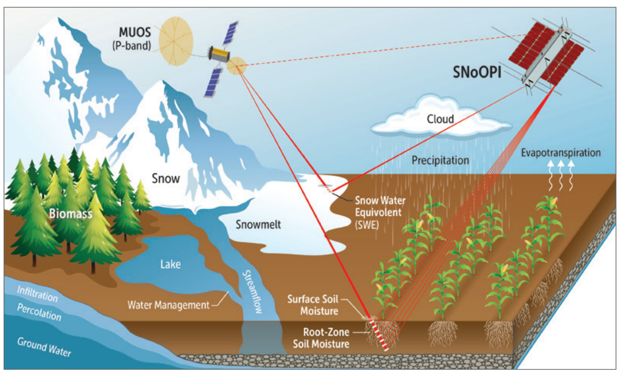
Plants absorb water down to about a meter below the surface and understanding the full distribution of water in this layer, known as the root zone soil moisture (RZSM), provides a critical link between surface hydrology and deeper processes. Globally mapping RZSM could directly aid our understanding of drainage characteristics, water uptake by plants, food production, and the connection between precipitation and fresh water availability. Our ability to map RZSM is severely limited by the shallow penetration of existing instrument and must rely upon predictions of the soil moisture at deeper levels using a technique known as model assimilation.

The key to sensing deeper into the soil is to use lower frequency radio signals. Unfortunately, this approach is not feasible using existing radiometers and radars, which would require very large (12-30 meter) antennas to meet resolution requirements and would also suffer from interference from other powerful sources (communication signals and space tracking radars) operating on such frequencies.

The Signals of Opportunity Airborne Demonstration (SoOp-AD) project showed that the same communication satellite transmissions that are the sources of this interference penetrate into the soil and reflect from

Earth's surface. By capturing these reflected signals and observing how they changed upon penetrating the soil, scientists can glean information about the RZSM profile at depths of 0 to 30 cm. This technique requires a substantially smaller antenna and results in power requirements that are orders of magnitude lower than traditional active radar, which requires a signal transmitter.

Another store of a large fraction of the Earth's water is snowpack, which has also proven difficult to measure from space. Similar methods to those demonstrated for RZSM measurement can be applied to sense the quantity of water stored in the snowpack, quantified as the Snow Water Equivalent (SWE).



▶ Concept for the CubeSat-based SigNals of Opportunity: P-band Investigation. (Image credit: Purdue University)

The SoOp-AD instrument was designed and developed by James Garrison at Purdue University and includes a P-band (240 – 270 GHz) and S-band (2332-2345 MHz) receiver system using a dual linear polarization antenna and two four-channel digital receivers. In late 2016, the project team tested the instrument on several flights onboard a NASA B-200 aircraft over instrumented field sites near the Little Washita watershed in Oklahoma. Further field experiments were conducted at the Purdue Agronomy Center for Research and Education (ACRE) to characterize reflected signals and demonstrate soil moisture retrievals under controlled conditions.

These experiments proved SoOp-AD to be a viable approach for next-generation soil measurements from space. PI, James Garrison, notes, "Understanding the water stored in snow and mapping moisture at the root zone are critical for understanding the Earth's water cycle." Reutilizing reflected "signals of opportunity" not only allows measurements to be made at previously inaccessible lower frequencies, the method does not require a dedicated transmitter. This approach enables an instrument concept that will be significantly lower in cost, mass, and power consumption than a comparable radar.

> **"Understanding the water stored in snow and mapping moisture at the root zone are critical for understanding the Earth's water cycle."**
>
> **– PI, Dr. James Garrison**

Further advancement of the P-band SoOp technique to TRL 6 or higher requires in-space demonstration in relevant environment conditions. On this basis, the project team was awarded a 2017 In-Space Validation of Earth Science Technologies (InVEST) grant to further demonstrate the concept on a CubeSat platform.

The SigNals of Opportunity: P-band Investigation (SNoOPI) will be the first demonstration of the P-band SoOp technique from orbit. SNoOPI will advance the prototype instrument to TRL7 to verify reflection coherence, robustness to the in-orbit radio-frequency interference (RFI) environment, and the ability to capture and process the transmitted signal in space. This demonstration is a necessary risk-reduction step on the path to employing this technology on a space-based science mission.

The SNoOPI instrument consists of three subsystems: a Low Noise Front End (LNFE) developed by NASA Goddard Space Flight Center, Digital Back End (DBE) developed by the NASA Jet Propulsion Laboratory, and antennas. Purdue University will lead the algorithm development and data processing and be responsible for running the Science Operations Center, where the data from the SNoOPI experiment will be collected, processed and evaluated. SNoOPI is scheduled for launch in January 2021.

Artist's concept of the Mars Helicopter, with the Mars 2020 rover in the background.

MARS HELICOPTER IS READY FOR EXTRATERRESTRIAL FLIGHT

PROJECT:
Mars Helicopter

SPONSORING ORGANIZATIONS:
SMD Mars Exploration Program, Aeronautics Research Mission Directorate, and Space Technology Mission Directorate

KEY POINTS:
The Mars Helicopter is a technology demonstration for the Mars 2020 rover mission, intended to show the feasibility and utility of using helicopters for Mars exploration. This technology may enable future missions to perform reconnaissance or independent science, and to access terrain not reachable by rovers and astronauts.

When NASA's next Mars rover sets out for the Red Planet in 2020, it will bring along a passenger. Nestled under the belly of the rover, the Mars Helicopter will be on a mission to notch a "first" for humankind: flying a helicopter on another planet.

By sending the helicopter to Mars as a technology demonstration, NASA aims to expand its exploration capabilities to include an aerial dimension, potentially opening new areas to exploration, and enabling faster reconnaissance for the benefit of future rovers or astronauts.

With a four-foot rotor and a weight of only four lbs, the Mars Helicopter's unique design is driven by the harsh realities of the Mars environment. The Martian atmosphere is extremely thin and cold; at only 1–2% the density of sea-level air and with temperatures down to -130˚ F, it resembles Earth's atmosphere at 100,000 ft—an altitude far beyond the capabilities of regular helicopters.

To make the Mars Helicopter a reality, researchers from NASA's Jet Propulsion Laboratory (JPL), NASA Ames Research Center, NASA Langley Research Center, and AeroVironment, Inc., worked together over several years to understand the unique challenges of flying on Mars, and to develop a viable vehicle design that is part aircraft and part spacecraft.

A crucial aspect of the design is to keep the mass as low as possible, but to carry enough power and energy to sustain the helicopter during flight. Recent technological advances in areas such as batteries and solar cells, miniaturized sensors and computers, and lightweight materials are key to achieving this goal. Many components of the Mars Helicopter were developed for the commercial cell phone and drone markets. They were qualified for the Mars Helicopter mission through testing in Mars-like temperatures and by subjecting them to radiation levels that would be experienced in space.

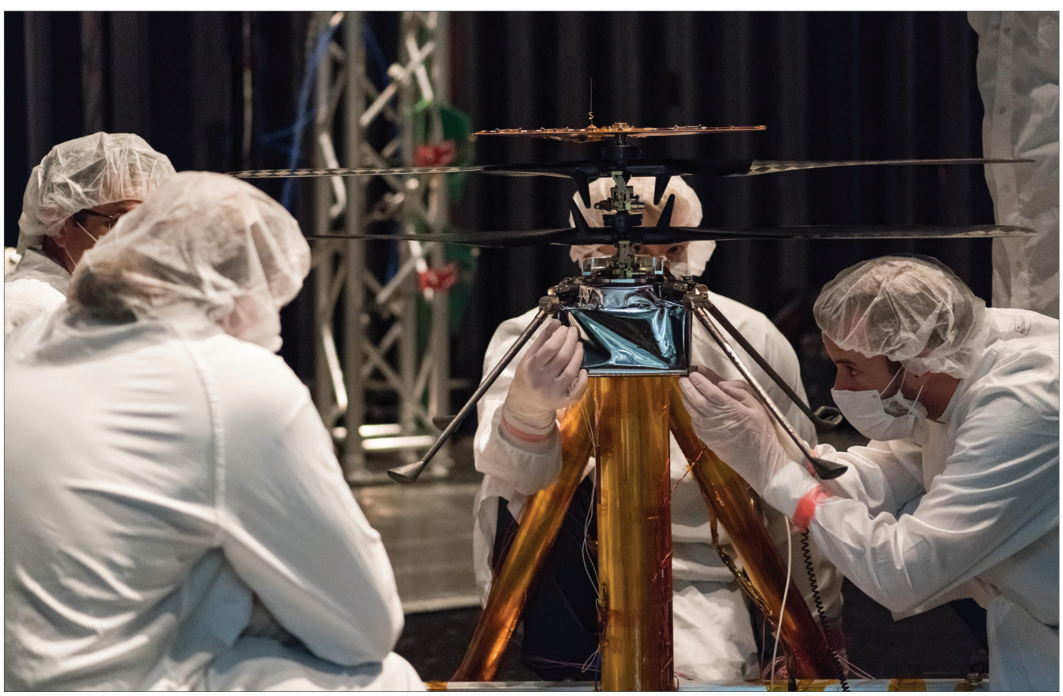
The Mars Helicopter is designed to operate independently on Mars, performing flights of about 90 s in duration at a height of 16 ft. The two rotors spin in opposite directions at approximately 2500 revolutions per minute (RPM). Between flights, the helicopter recharges its batteries using an onboard solar panel. A 12-Megapixel camera takes pictures during flight, which are beamed back to the rover for relay to Earth. During the cold Martian nights, the batteries and sensitive electronics are kept warm inside a heated and insulated fuselage.

During flight the helicopter must navigate with full autonomy, unassisted by humans and without GPS or other navigation aids. JPL researchers developed a vision-based navigation system for the helicopter, which analyzes camera images and combines the information with measurements from an inertial measurement unit and an altimeter to keep track of the helicopter's position, velocity, and attitude. To

▶ The finalized Mars Helicopter Flight Model.

develop the control system for the helicopter, the team performed extensive modeling and simulation, as well as low-density experiments, to determine how the thin atmosphere would affect the response of the helicopter to control inputs, wind, and gusts.

The team's "Wright brothers' moment" came in May 2016, when controlled flight was achieved with a test vehicle inside JPL's Twenty-Five-Foot Space Simulator, a large vacuum chamber where the conditions of the Martian atmosphere were replicated. In 2018, tests were performed with emulated Martian winds, produced using nearly 900 fans. Furthermore, the Mars Helicopter Flight Model, which will be sent to Mars, was built and tested, before performing its maiden hover flight in early 2019. It will now be integrated with the rover and await the chance to fly again—this time on Mars.



▶ Members of the Mars Helicopter team preparing the helicopter for a test in the Twenty-Five-Foot Space Simulator.

FOXSI'S X-RAY OPTICS AND DETECTORS PUT THE SUN IN FOCUS

PROJECT:
Focusing Optics X-ray Solar Imager (FOXSI) sounding rocket

SPONSORING ORGANIZATION:
Heliophysics Division's H-TIDeS Program

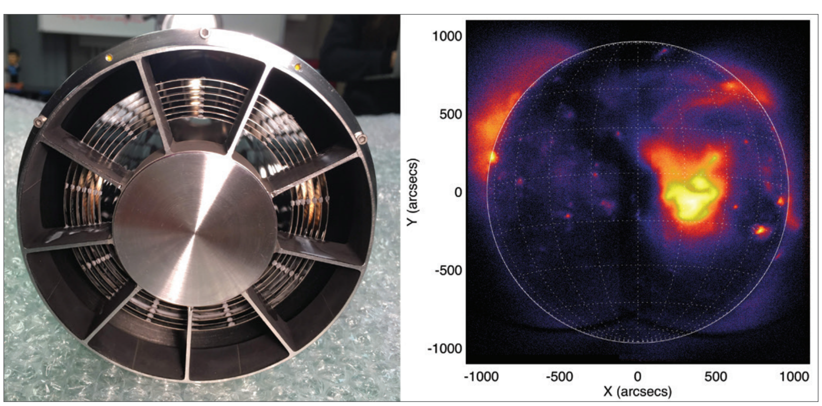
PROJECT LEAD:
Dr. Lindsay Glesener, University of Minnesota

KEY POINTS:
This third flight of the FOXSI experiment featured direct-focusing X-ray optics, 3D-printed collimating devices for limiting background, and high-resolution X-ray detectors. This technology will enable high-fidelity X-ray imaging in astronomy and other fields.

X-rays from the Sun help us probe the highest-energy phenomena that occur in our solar system, including solar storms and their origins. The Sun presents some unique challenges to researchers attempting to unravel its high-energy behavior. To deal with these challenges, a sounding rocket experiment team has developed an array of new technologies that can reveal how the Sun emits high-energy radiation, plasma, and particles.

The Sun gives off abundant X-rays from its fiery, multimillion-degree corona (the outermost layer of the solar atmosphere) and poses particular challenges for X-ray imaging. During solar flares, which temporarily heat up the corona locally to many tens of millions of degrees, a multitude of X-rays are radiated into space. Yet the part of this emission that most intrigues solar astrophysicists is the faintest X-ray flux, which can reveal how solar flares are triggered, how they transfer energy, and how they accelerate particles up to extraordinarily high energies.

Solar flares are often associated with coronal mass ejections, in which huge volumes of plasma are kicked out of the corona and sent off into interplanetary space. When Earth-directed, these ejections can cause geomagnetic storms with the potential to threaten spacecraft, astronauts, and power grids. Understanding the origins of these events is therefore of the utmost importance. For this reason, solar astrophysicists are searching for faint X-rays emanating from the hidden sites from which these events originate to understand the keys to energy release in the corona. To observe this faint emission in the tumultuous context of a solar flare is a demanding requirement for any X-ray technology.



▶ The FOXSI X-ray mirror (left) and an X-ray image of the Sun captured by the Photon Energy Imager in soft X-rays (PhoEnIX), one of FOXSI-3's new cameras (right).

The Focusing Optics X-ray Solar Imager, or FOXSI, is a sounding rocket experiment that takes a novel approach to this challenge. Traditional reflecting or refractive telescopes do not work for X-rays because the rays tend to simply pass through or absorb in the medium. Therefore, past missions had to use indirect methods to image high-energy X-ray sources in the sky. However, it is possible to reflect X-rays using a mirror with a small angle of incidence and a perfect shape; this method is used by NASA's Nuclear Spectroscopic

▶ The FOXSI-3 team includes postdoctoral researchers, graduate students, and undergraduate students. These young researchers took advantage of a rare opportunity to build, test, and fly a NASA experiment, participated in all aspects of the preparation and flight, and are now the lead scientists analyzing the results.

Telescope Array (NuSTAR) mission as well as several instruments that operate at lower energies. The challenge for FOXSI was to take this technology and adapt it for observing the Sun, which produces a wider range of brightnesses and more complex, intricate sources than any other astronomical object.

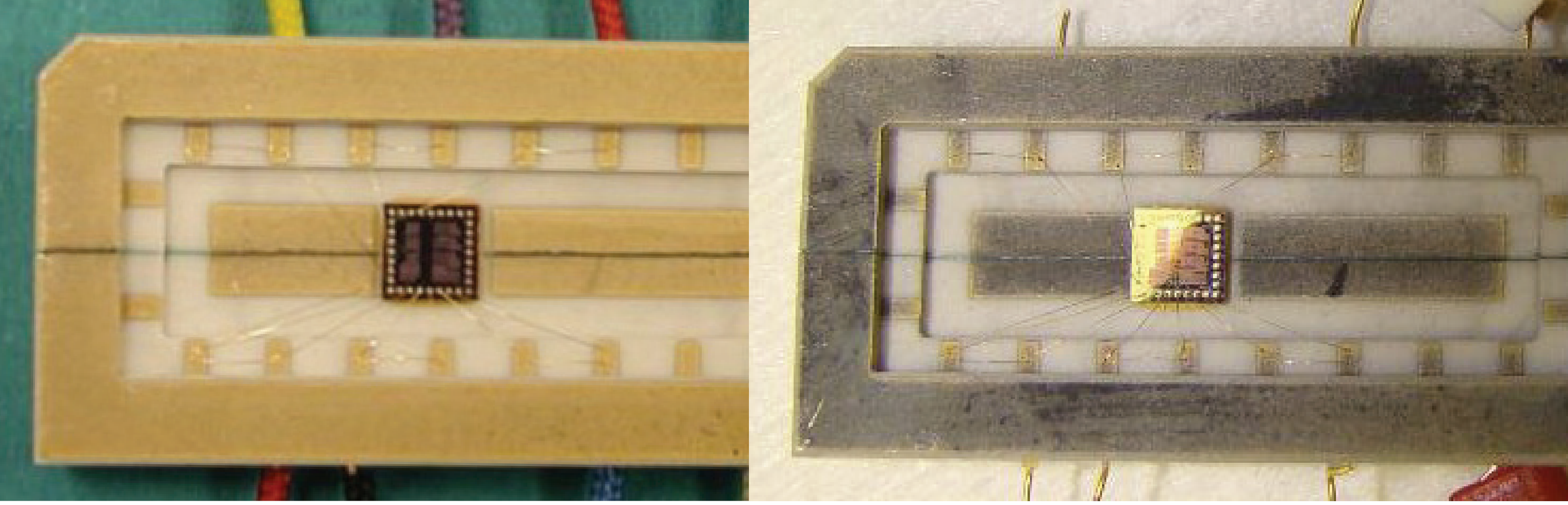
To accomplish this task, FOXSI features several novel, cutting-edge technologies. The heart of FOXSI's technology is its reflecting mirrors that are specially designed for solar observations. PI, Dr. Lindsay Glesener, explains the FOXSI approach: "Rather than just building a bigger or improved mirror, this new focusing technology is an entirely transformative way of measuring X-rays from the Sun." FOXSI's mirrors are produced at NASA's Marshall Space Flight Center using a "fast replication" process that involves electroforming nickel onto carefully shaped and polished molds. Use of these molds means that no further "hand polishing" must be performed on each individual mirror, drastically cutting down the effort and expense needed to produce the mirror sets. For its third flight, FOXSI-3 also included new collimating structures to reduce instrumental background. These collimators, produced by 3D-printing a honeycomb structure out of a titanium alloy, were designed by the National Astronomical Observatory of Japan and Nagoya University and were fabricated by the Toray company of Japan.

Lastly, FOXSI-3 features three different kinds of X-ray cameras. One camera made of silicon and another made of cadmium telluride are both designed to measure the highest energy X-rays one by one, carefully recording positions, energies, and times of every single X-ray that enters the instrument. The third camera, called the Photon Energy Imager in soft X-rays (PhoEnIX), does the same for X-rays of lower energies, which is an even harder job; to measure the bright X-ray emission at these energies, a fast camera rate is needed.

Using these new technologies, FOXSI-3 flew successfully on September 7, 2018, and produced the first focused images of the Sun across a wide range of energies in "photon counting" mode – in which every single X-ray is individually recorded and analyzed. This method of measurement will allow solar astrophysicists to achieve their goal of measuring the bright X-ray emission from solar flares, while simultaneously capturing the faint traces of energy release and particle acceleration that instigate the events.

When this technology is eventually realized on a spacecraft mission, scientists will be able to tell how solar eruptions start, how the vast amounts of energy are transferred, and how particles are accelerated and escape the Sun. The technology pioneered on this sounding rocket experiment is already forming the basis of plans for a FOXSI spacecraft. In addition, the technology developed for FOXSI will transfer to other fields, allowing for high-energy X-ray mirrors and cameras to be used for medical and other applications.

FOXSI-3 is a collaboration between the University of Minnesota, University of California Berkeley, NASA Marshall Space Flight Center, NASA Goddard Space Flight Center, University of Tokyo/Kavli Institute for the Physics and Mathematics of the Universe, Nagoya University, Tokyo University of Science, Japan Aerospace Exploration Agency /Institute of Space and Astronautical Science, and the National Astronomical Observatory of Japan. More information is available at foxsi.umn.edu.



▶ An advanced silicon carbide integrated circuit before a 60-day test unsheltered in harsh Venus surface conditions (left) and the same circuit (right) still going strong after the test.

INTEGRATED CIRCUITS TO ENABLE EXPLORATION OF THE HARSHEST ENVIRONMENTS IN THE SOLAR SYSTEM

PROJECT:
High Temperature Memory Electronics for Long-Lived Venus Missions

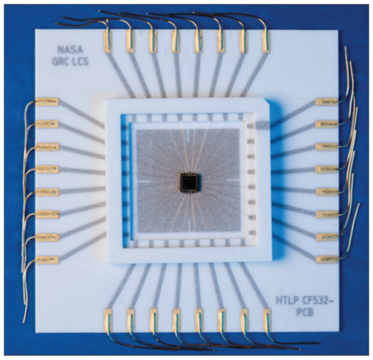
SPONSORING ORGANIZATION:
Planetary Science Division's HOTTech Program

PROJECT LEAD:
Philip Neudeck, NASA Glenn Research Center

KEY POINTS:
Newly developed silicon carbide electronics have operated in ovens for over a year at 500°C and for 60 days in simulated Venus surface conditions. This technology is key to enable future extended missions to explore the Venus surface and other harsh space environments.

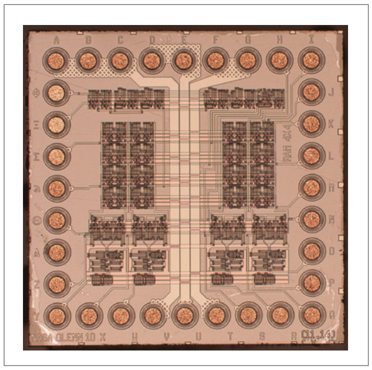
The capability to operate in harsh environments is crucial for spacecraft to explore the most forbidding regions in the solar system. Recent advances in silicon carbide (SiC) electronics have changed the paradigm of what is possible for exploration of such environments, including the surface of Venus where spacecraft will experience scorching temperatures and crushing pressure. This technology also holds promise for enabling missions to other harsh environments such as the high-radiation, yet thermally cold, surface of Europa or the atmospheres of gas giants.

Previous surface exploration on Venus was determined by the capabilities of conventional silicon-based electronics whose survivability—despite high-mass sheltering from the brutal temperature and pressure conditions—was limited to about two hours. A team at NASA Glenn Research Center (GRC) is developing a new generation of electronics that can operate for extended periods of time in these and other harsh conditions without the need for environmental sheltering. This technology opens the door for planetary exploration that was not possible even just a few years ago.



▶ Packaging technology able to survive the 465°C, 92- atmosphere, caustic environment of the Venus surface is enabling new planetary exploration.

One possible mission platform that could employ these new electronics is the Long-Lived In-Situ Solar System Explorer (LLISSE)—a small probe system that will



▶ A 3 mm x 3 mm Random Access Memory (RAM) IC (shown prior to packaging) has operated for over a year at 500°C in an oven.

investigate the Venus surface for a lengthy period. Such a probe would weigh 50-times less than previous Venus landers, which relied on high-mass sheltering to protect standard silicon electronics. LLISSE is planned to operate on the 465°C, 92-atmosphere, caustic environment of the Venus surface for 60 days or more, providing measurements and uniquely contributing to our understanding of the planet. Key to LLISSE operation are the SiC electronics that are required for sensors, data handling, communications, and power management, and that must sustainably operate for months in the Venus environment without sheltering. Although the complexity of these new SiC electronics is presently comparable to that of standard commercial electronics in the 1970s, such electronics at that time nevertheless made possible the Viking and Voyager probes that successfully pioneered historic breakthroughs during their planetary exploration missions.

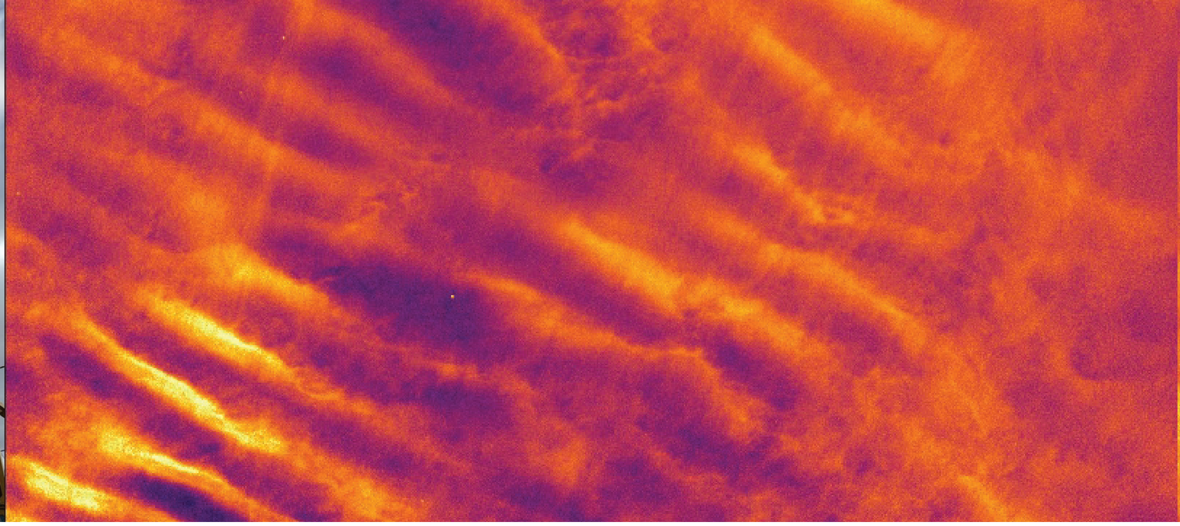
The GRC team significantly advanced these SiC electronics in 2018. For example, the team conducted the world's first demonstration of stable electrical operation of more than 100 transistor integrated circuit (IC) chips for over one year at 500 °C. One of these SiC ICs was the world's-first memory chip to survive and function in these conditions. This memory chip, a Random Access Memory (RAM) chip using 195 transistors, continued to store and process information after 1.5 years in an oven at 500 °C. The level of complexity of these new electronics is more than a factor of seven beyond what was previously shown durable at 500 °C. Furthermore, 175 transistor clock ICs were successfully operated in harsh Venus surface conditions for 60 days, unshielded and open to the environment without fail until the Venus chamber scheduling dictated conclusion of testing.

In parallel, the team also demonstrated the resilience of these SiC ICs in both heavy-radiation environments, as well as very cold environments. Shielding of conventional silicon-based electronics in high-radiation environments has been a complicating factor for potential missions such as Europa probes and landers, so there has been a drive to provide electronics which do not need shielding.

While further analysis and testing is needed, initial radiation test results collected in 2018 have confirmed theoretical assertions that these SiC ICs are capable of operating for years in the high-radiation environments of the Jovian moons without the need for radiation shielding. Combined with the recently demonstrated ability of these SiC ICs to operate at temperatures down to -190 °C, these results introduce the possibility of SiC electronics providing solutions for selected operations in future Europa missions.

The possible impact of SiC electronics on not only planetary exploration, but on a range of commercial and Earth-based applications is just beginning to be realized. This technology can enable intelligent systems in a revolutionary new range of applications and environments, e.g., new capabilities in jet engine systems. In fact, this technology won a 2018 R&D 100 Award—a prestigious international award that honors revolutionary ideas in science and technology. NASA's advancements in SiC ICs are ongoing, and the complexity of the electronics is increasing at a significant rate. These new electronics have the potential to enable new capabilities and missions across the solar system.

▶ SiC IC Memory Team members depositing chip interconnect metal in the NASA GRC Microsystems Fabrication Laboratory.

▶ The PMC Turbo payload positioned for launch at Esrange (left); a PMC image of strong and interacting Kelvin-Helmholtz instabilities that have wavelengths of ~4 km, colorized to enhance sensitivity to small features (right).

BALLOON-BORNE IMAGING CAPTURES TURBULENCE SOURCES REVEALED IN POLAR MESOSPHERIC CLOUDS

PROJECT:

Polar Mesospheric Cloud Turbulence experiment (PMC Turbo)

SPONSORING ORGANIZATION:

Heliophysics Division's H-TIDeS Program

PROJECT LEADS:

Dave Fritts, GATS with Co-I Amber Miller, Columbia University

KEY POINTS:

The balloon-borne PMC Turbo experiment successfully provided information about small-scale instabilities and turbulence in the mesosphere that will ultimately contribute to improving weather and climate models.

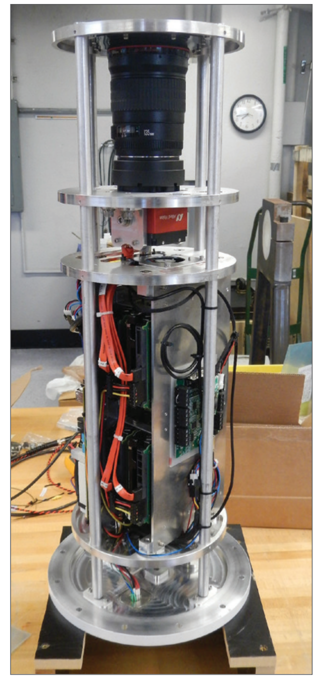
The thin remote Polar Mesospheric Cloud (PMC) layer at an ~82-km altitude in the summer polar atmosphere is possibly the best place on Earth to study the sources and effects of turbulence in geophysical fluids – key small-scale processes that play major roles in weather and climate. Images from the balloon-borne PMC Turbulence experiment (PMC Turbo) are yielding insights into how gravity wave and turbulence processes transport and deposit energy and momentum throughout the atmosphere.

Comprised of seven PMC imagers and a Rayleigh lidar, PMC Turbo provided overlapping large and small imager fields-of-view and PMC altitudes and displacements, which are enabling analyses of events extending from gravity wave sources at scales as large as 100 km to the inner scale of turbulence at ~20 m. PMC Turbo was launched on July 8, 2018 from Esrange, Sweden and landed almost six days later in northern Canada after collecting over two million high-resolution PMC images.

PMC Turbo imagers in separate pressure vessels were configured to operate as an integrated system or autonomously as piggyback payloads and/or individual ground systems. Each pressure vessel contained a high-resolution camera, a computer control system, and 32 TB of data storage. Computer software allowed each system to coordinate the full imaging suite and manage flight control and communications. The PMC Turbo imagers, redundant flight control capabilities, and a dual-circuit power system provided major redundancies and ensured collection of significant PMC imaging even in the event of multiple subsystem failures, none of which occurred. The successful PMC Turbo payload development, integration, testing, and flight program was largely performed by the graduate students and research scientists pictured in the launch site photo below.

To augment the scientific benefits of PMC Turbo, the payload hosted the first Rayleigh lidar to fly successfully aboard a stratospheric balloon platform. The lidar measured the PMC backscatter profile and vertical displacements at the PMC layer, and quantified gravity wave temperature perturbations in the stratosphere below the PMC layer. The lidar was fabricated, integrated, and tested by a team at the German Aerospace Center (DLR). Lidar backscatter profiles and derived gravity wave temperature perturbations have provided valuable additions to PMC Turbo analyses to date.

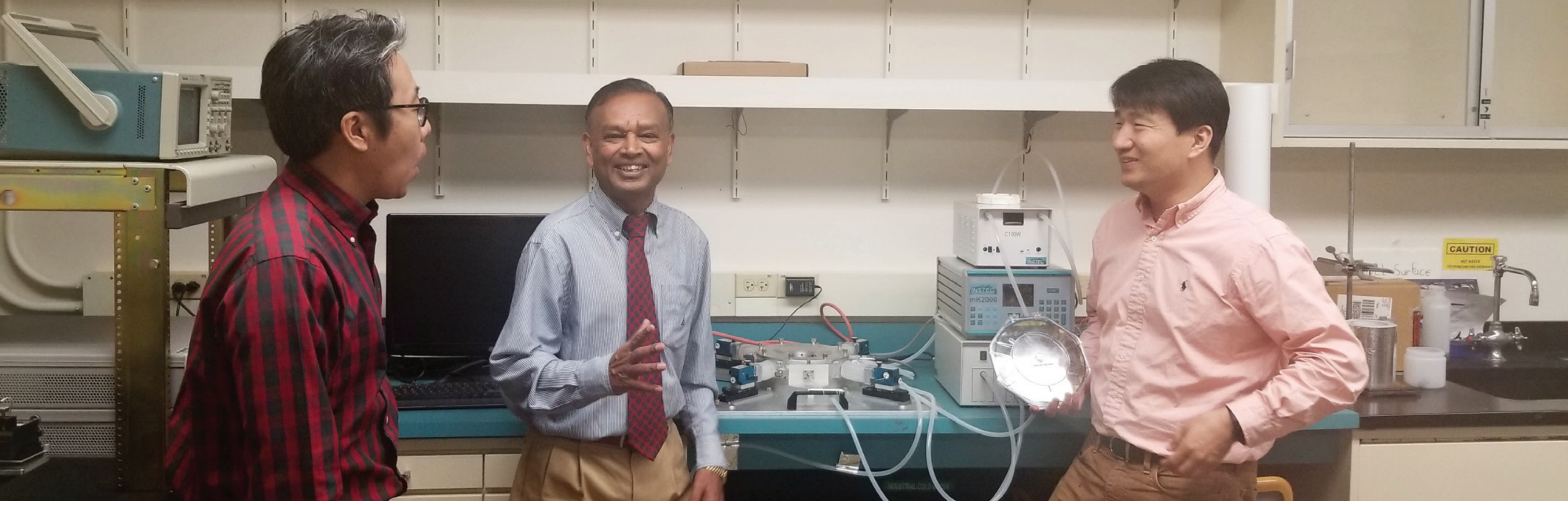
Small-scale instabilities and turbulence account for deposition of energy and momentum transported throughout the atmosphere and other fluid systems by gravity waves. These dynamics play key roles in weather and climate but are poorly represented in weather and climate models at present. Despite the remote location and the challenges inherent to observing these phenomena, our observations will enable studies of the dynamics revealed in PMCs that can guide improvements in weather and climate models, which could yield significant societal benefits. The information provided by PMC Turbo could also enable more accurate modeling and increase our understanding of other fluid systems, such as those in oceans, lakes, other planetary atmospheres, and stellar interiors.



▶ PMC turbo pressure vessel imaging system components: lens, camera, computer and data storage.

PMC Turbo was recovered in Canada with all key instruments and systems intact. The pressure vessels and lidar are ready for another flight. Given the results of analyses to date, the PMC Turbo team expects multiple, valuable studies to result. Analyses have also revealed how even more comprehensive and beneficial data could be obtained with additional instrumentation, an improved imaging configuration, and a flight at a higher latitude over Antarctica where PMCs are brighter and more continuous. The team is considering new instrument options to further expand the measurement capabilities and anticipates a new flight proposal at the next opportunity.

▶ Christopher Geach (University of Minnesota), Bernd Kaifler (German Aerospace Center), Biff Williams (GATS), and Bjorn Kjellstrand (Columbia University), left to right, prior to launch at Esrange.



▶ The nanoscale vacuum channel transistor (NVCT) team in the lab at NASA Ames. From left to right: Dong-il Moon, Meyya Meyyappan, and Jin-Woo Han.

NANOSCALE VACUUM ELECTRONICS: BACK TO THE FUTURE?

PROJECT:
Nanoscale vacuum channel transistor (NVCT)

SPONSORING ORGANIZATION:
Planetary Science Division's Icy Satellites Program

PROJECT LEAD:
Dr. Meyya Meyyappan, NASA Ames Research Center

KEY POINTS:
To help protect future space assets from dangerous effects that arise from radiation exposure, NASA is developing a new series of vacuum electronics that are ultra-small, easy to manufacture, and immune to radiation damage.

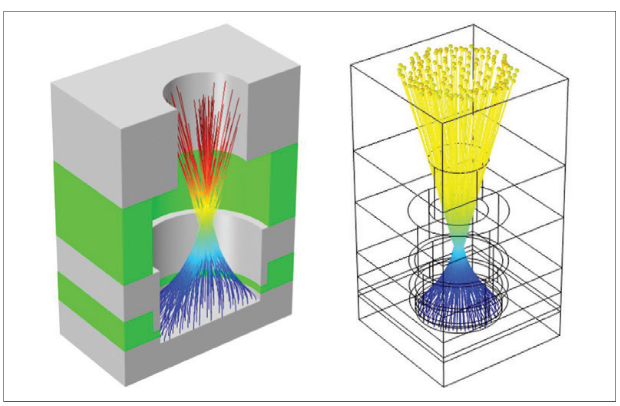
All space missions face a high risk of radiation-induced damage to electronics. Unfortunately, the current strategies employed to limit radiation exposure all introduce various mission constraints. NASA is exploring use of an "old school" technology—vacuum electronics—combined with modern techniques to protect the Agency's important space assets without restricting mission parameters.

NASA implements various strategies to avoid radiation impacts to missions including: (1) limiting the flight and exploration path to minimize radiation exposure, (2) use of radiation shielding based on a metal chassis, and (3) incorporating chip designs with radiation awareness. However, all of these tactics introduce mission constraints. Limiting the exploration path leads to delays and constrains the exploration area. Furthermore, it is intrinsically impossible to avoid unexpected radiation exposure. The metal radiation shield adds significant weight, impacting the launch cost. A radiation-aware design is expensive and limits the available hardware options because not all the required parts can be found in space-grade pool of available equipment. Another serious emerging problem is the dwindling number of U.S. companies supplying radiation-hardened electronics due to the low-volume nature of the business.

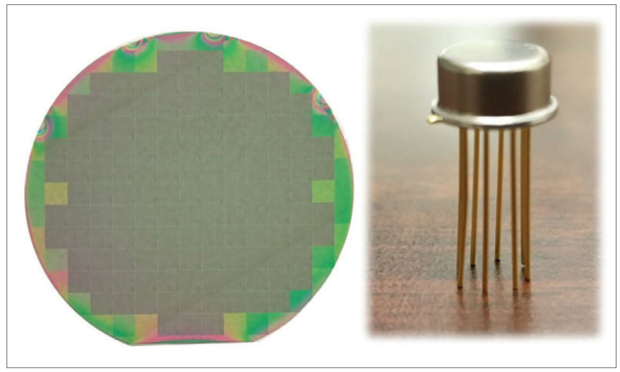
Vacuum devices of the early electronics era were immune to space radiation but they were bulky and energy-hungry. More importantly, they were not amenable to large-scale manufacturing, as we know today. Silicon-based integrated circuits successfully demonstrated their potential to overcome the shortcomings of the vacuum devices, ushering in the modern electronics revolution and sunsetting the vacuum electronics era. Except, all modern electronics devices using silicon, gallium arsenide, and other materials are vulnerable to radiation, posing challenges to space mission designers to come up with ways to mitigate the radiation impact. It is not uncommon for missions to incorporate electronics technologies several generations behind the state-of-the-art due to the time-consuming process associated with finding the right solution to protect the electronics from the deleterious effects of space radiation.

A team at NASA Ames is developing the nanoscale vacuum channel transistor (NVCT) by combining the best of vacuum electronics—known for radiation immunity—with modern integrated circuit manufacturing practices that excel in making ultra-small devices. In a nutshell, the semiconductor channel in a transistor is replaced with an empty gap in the NVCT. Unlike the channels in a semiconductor, which suffer from lattice scattering, this vacuum channel enables ultra-high electron velocities in the NVCT. NVCTs can be fabricated using any of the common semiconductor materials such as silicon, gallium arsenide, silicon carbide and others.

In the last 18 months, the Ames team has successfully fabricated silicon as well as silicon carbide NVCTs on 150-200-mm wafers with dimensions comparable to conventional metal-oxide semiconductor field-effect transistors (MOSFETs). The smallest silicon NVCT has a 50-nm source-drain distance with a surround gate. To make the NVCT drive currents comparable to conventional MOSFET devices, multiple emitter tips are needed. For this reason, the team chose a vertical configuration for the NVCT with the source pad hosting multiple emitter tips at the bottom, a



▶ Simulated trajectory of field-emitted electrons within the NVCT; electrons are emitted from the source pad at the bottom and collected at the top with the surround gate controlling the flow.



▶ 50-mm silicon carbide wafer with fabricated NVCTs and an individual packaged device.

common collector at the top, and a gate wrapping around the channel for ideal electrostatic control. The NVCT device current was shown to scale linearly with the number of emitter tips, offering design flexibility for achieving desired mA current levels. Unoptimized initial NVCT devices show a potential of 0.5 THz operation. Exposure to radiations at doses typically experienced by space missions (a few tens of MRad gamma radiation and 10 MeV fast neutrons) showed negligible impact on device characteristics.

These successful results at the transistor level are encouraging, and now the NASA team is developing circuit-level vacuum devices. The current effort involves adding on-chip resistors and capacitors to the wafers hosting the NVCTs to facilitate assembly of functional circuits. The next planned step will demonstrate a working “flip-flop” circuit and assess the radiation impact on that circuit.

Radiation-immune nanoscale vacuum electronics will be highly valuable to many NASA missions, including exploration missions to Europa, which will face extreme radiation environments and low temperatures. Measures similar to the Juno Radiation Vault—a titanium compartment that protects the electronics on the Juno spacecraft—may be needed to protect vulnerable electronics in these missions. Such measures increase weight and mission complexity and do not entirely ensure radiation immunity. Electronics failure could lead to mission failure, thus the NVCT effort could have a significant impact on future missions by eliminating the need for such vaults.

A HIGH RESOLUTION "COLOR" X-RAY CAMERA WITH THOUSANDS OF PIXELS

PROJECT:
Demonstration model of the Athena X-ray Integral Field Unit (X-IFU)

SPONSORING ORGANIZATION:
Astrophysics Division's PCOS Program

PROJECT LEAD:
Dr. Caroline Kilbourne, NASA GSFC

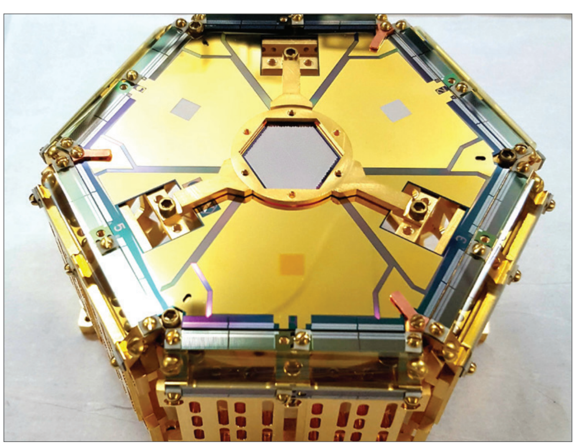
KEY POINTS:
An X-ray camera is being developed with 3168 pixels and ground-breaking capability to resolve different "colors" of X-rays. This technology will allow observations of the dynamics and composition of hot energetic material in galaxy clusters and around black holes. Scientists can use these images to learn about the formation and evolution of these complex cosmic objects.

Some of the most fascinating objects in the universe are made up of hot energetic material that emit X-rays. NASA is part of an international collaboration developing a camera capable of imaging these systems using microcalorimeter pixels. This camera will be part of the European Space Agency's (ESA) Advanced Telescope for High ENergy Astrophysics (ATHENA). Spatial resolution will be enabled by the presence of 1000s of these pixels laid out in an array, and the exquisite energy resolution of each pixel will give the images their "color."

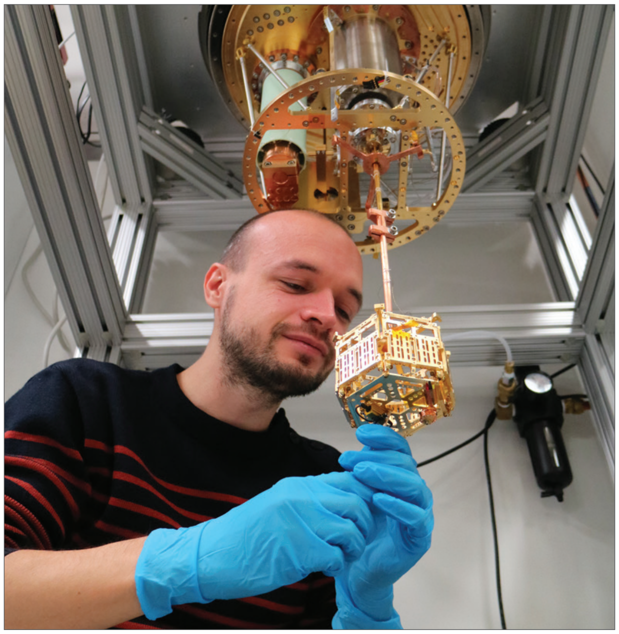
In an X-ray microcalorimeter, an X-ray absorber is connected to a very sensitive thermometer. When an X-ray is absorbed in the device it causes a small change in the temperature that is read by the thermometer. The greater the energy of the X-ray absorbed, the larger the change in temperature, and therefore, it is possible to determine the energy or "color" of the incident X-ray.

To achieve the best energy (color) resolution, the microcalorimeters are cooled to less than 0.1K and the temperature is monitored by measuring the current flowing through a superconductor that is held just at the point of transition from a normal metal to a superconductor. These transition-edge sensor (TES) microcalorimeters are then able to measure the energy of 6 KeV X-rays with a resolution of less than 2.5 eV, or 1 part in 2400.

X-ray microcalorimeter technology has been steadily improving since its inception three decades ago. The NASA/Japan Aerospace Exploration Agency (JAXA) Soft X-ray Spectrometer microcalorimeter instrument onboard the Hitomi satellite flew with 36 pixels. The X-ray integral field unit (X-IFU) instrument on ATHENA is baselined to have an array of 3168 TES microcalorimeter pixels fabricated at NASA and developed as part of a longstanding collaboration between NASA, the National Institute of Standards and Technology (NIST), and Stanford University. Dr. Caroline Kilbourne notes, "Combining imaging with spectroscopy, the X-IFU instrument will probe dynamics and composition within spatially extended cosmic objects such as supernova remnants and galaxy clusters with unprecedented sensitivity."

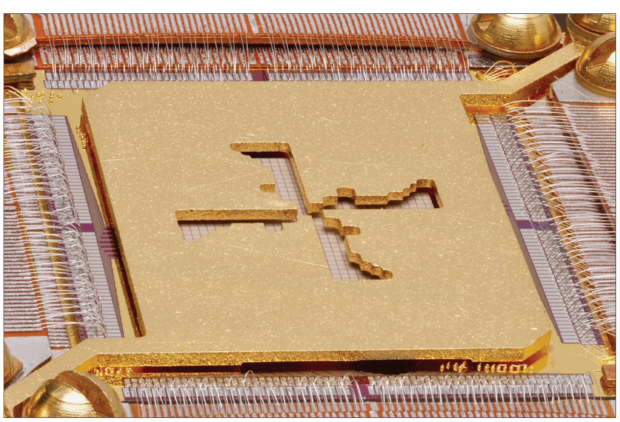


A prototype full-size TES microcalorimeter array mounted on a testing platform that mimics the focal plane assembly design for the ATHENA mission.



Dr. Antoine Miniussi at NASA Goddard Space Flight Center installing the assembly to test X-IFU prototype arrays.

The technology baselined by ESA to read out the X-ray detector pixels in the X-IFU uses an alternating-current (AC) bias. This process is fundamentally different from the direct-current (DC) readout that has been the focus of TES development at NASA historically. Over the last two years several changes have been made to the TES design to improve the resolution of the detectors with AC bias to enable the very best performance. NASA's collaborators at the Netherlands Institute for Space Research (SRON) recently achieved, for the first time, a resolution of 2.6 eV in 9 pixels, using NASA-fabricated devices and their AC bias readout technology. NASA has now delivered an array of 1000 pixels to SRON to demonstrate the performance on a larger scale.

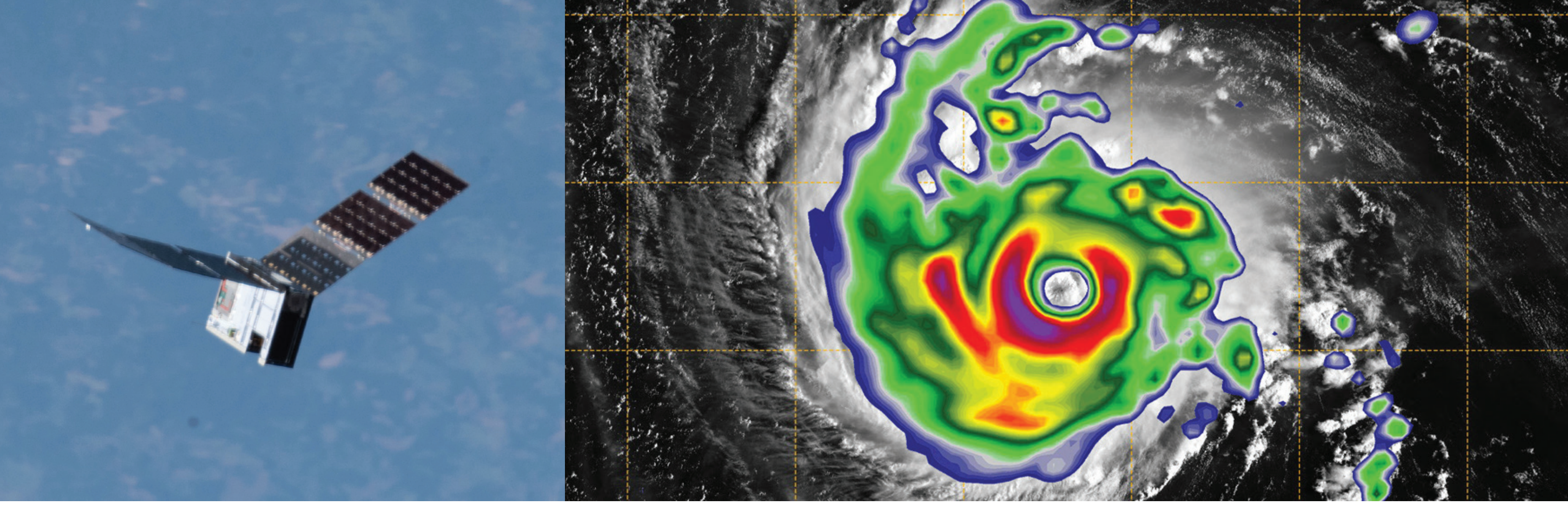


A kilo-pixel array below a collimator being tested with DC bias readout.

Meanwhile, the NASA/NIST/Stanford team has continued to develop the detector design and associated technology for DC readout. This option may serve as a backup for X-IFU, if necessary. This work has led to the demonstration of the energy resolution required for X-IFU simultaneously in 85 pixels. While this demonstration shows that the required energy resolution can be achieved on the scale of 10 to 100 pixels, the collaborators are now focusing on optimizations to allow the required performance simultaneously on the scale of 1000s of pixels required for X-IFU. The first prototype full-scale arrays, with 3168 pixels placed at the center of a hexagonal wafer, have been fabricated, and are being integrated into a new test apparatus, which will mimic the focal plane assembly of the final X-IFU instrument. Over the next year the team will be testing these full-scale wafers and continuing to improve the detector design to achieve the best possible performance with AC and DC bias.

"Combining imaging with spectroscopy, the X-IFU instrument will probe dynamics and composition within spatially extended cosmic objects such as supernova remnants and galaxy clusters with unprecedented sensitivity."

- Dr. Caroline Kilbourne, NASA GSFC



▶ The TEMPEST-D CubeSat after deployment from the International Space Station (ISS) on July 13, 2018 (left). Shortly after becoming fully operational, TEMPEST-D captured this first full-swath image of Hurricane Florence on September 11, 2018 (right). The colors reveal the eye of the storm, surrounded by towering, intense rain bands. (Visual image of the storm clouds on right taken by the National Oceanic and Atmospheric Administration's [NOAA] Geostationary Operational Environmental Satellite [GOES]: NASA/NOAA/Naval Research Laboratory Monterey/JPL-Caltech)

BIG WEATHER DATA FROM A TINY CUBESAT

PROJECT:
Temporal Experiment for Storms and Tropical Systems Demonstration (TEMPEST-D)

SPONSORING ORGANIZATION:
Earth Science Division's InVEST Program

PROJECT LEAD:
Dr. Steven C. Reising, Colorado State University

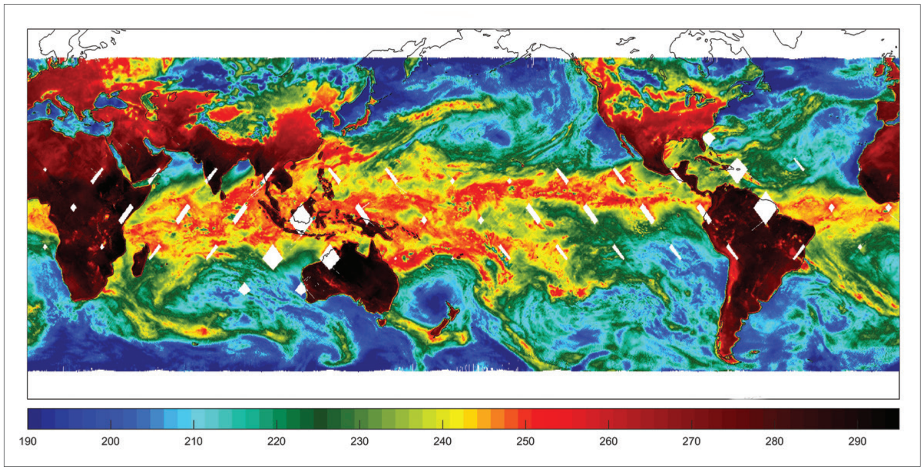
KEY POINTS:
The TEMPEST-D CubeSat demonstrated low-cost, low-risk, millimeter wave radiometer technology that will enable constellations of small satellites to provide the first temporal observations of cloud and precipitation processes on a global scale.

Imaging microwave radiometers on large government satellites have been providing critical weather data for over 40 years. The NASA Earth Science Division's InVEST Program has demonstrated a new radiometer that fits on a CubeSat, providing direct evidence that this miniaturized sensor technology can provide observations with the same high quality as those obtained from larger, heritage instruments on operational weather satellites.

This low-cost technology opens the door to development of a fleet of CubeSats that can provide nearly continuous monitoring of Earth's weather, including severe storms and hurricanes. PI Steven Reising stated, "With a train of TEMPEST CubeSats, we will be able to take time samples every three to five minutes to see how a storm develops." The technology also enables exciting new scientific investigations of rapidly developing atmospheric processes leading to severe weather affecting life and property through high winds, hail, lightning, and flash floods.

The Temporal Experiment for Storms and Tropical Systems Demonstration (TEMPEST-D) CubeSat has demonstrated a new five-frequency, millimeter-wave (87, 164, 174, 178 and 181 GHz) imaging radiometer to observe the temporal evolution of clouds and precipitation processes. TEMPEST-D took some of its first data over Hurricane Florence on September 11, 2018, and has been continuously imaging the interior of clouds and precipitation ever since.

> "With a train of TEMPEST CubeSats, we will be able to take time samples every three to five minutes to see how a storm develops."
>
> – PI, Dr. Steven Reising



▶ TEMPEST-D 87-GHz global brightness temperature measurements (in Kelvin) acquired on December 8-9, 2018.

component technologies can function well in low Earth orbit. The radiometer receivers use state-of-the-art indium phosphide (InP) high-electron-mobility transistor (HEMT) low-noise amplifiers for the first time in low-power receivers for Earth science. This new technology makes the TEMPEST-D radiometer the lowest-noise sensor currently in Earth orbit at these operating frequencies.

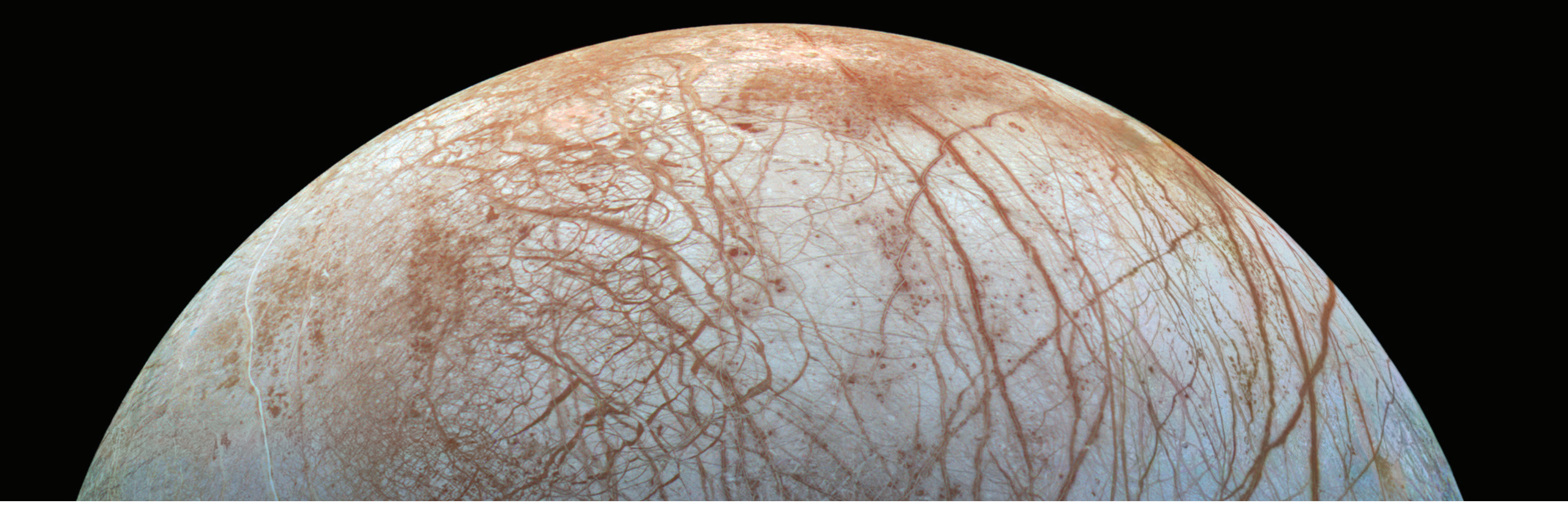
While TEMPEST-D is significantly smaller than prior microwave weather sensors, it does not sacrifice data quality. Its success results from the original science mission that inspired the design of the TEMPEST sensor. Resolving small changes in developing storms requires the sensor to use the same high-quality calibration sources found in the much larger operational sensors, albeit engineered to fit both the sensor and the calibration sources into a small volume.

TEMPEST-D is not only demonstrating that high-quality observations of clouds, precipitation, and humidity can come from a satellite the size of a cereal box, it is also proving that new radiometer

▶ TEMPEST-D Team Members at the launch of Orbital ATK's 9th commercial resupply mission from NASA Wallops to the ISS on May 21, 2018. From left to right: Rudi Bendig (JPL), Mary Soria (JPL), Sharmila Padmanabhan (JPL), Ann Batchelor (CSU), Bob Bauer (NASA ESTO Program Manager), Steven Reising (CSU), and Cate Heneghan (JPL).

The TEMPEST-D mission was initiated as a partnership among Colorado State University (CSU, lead institution and validation), NASA/Caltech Jet Propulsion Laboratory (instrument and calibration) and Blue Canyon Technologies (spacecraft and mission operations). The TEMPEST-D satellite was launched on May 21, 2018 on Orbital ATK's commercial resupply mission to the ISS and successfully deployed from the ISS on July 13, 2018, from an initial orbit with 400-km altitude and 51.6° inclination.

The high quality of TEMPEST-D data was demonstrated by comparing TEMPEST-D observations with those from four sensors (operated by NASA, NOAA, and the European Organisation for the Exploitation of Meteorological Satellites) that are widely used in the atmospheric science and weather forecasting communities. CSU scientists compared TEMPEST-D data acquired between October and December 2018 with data from the reference sensors, which are also in low-Earth orbit. This process demonstrated that TEMPEST-D data quality is indistinguishable from that of the data provided by these well-established radiometers, even though the TEMPEST-D CubeSat is a fraction of the size and costs significantly less.



▶ The search for life in the solar system includes studying the interfaces between water and rock—thought to be in abundance under the icy mantel of Jupiter's moon Europa. PESTO is developing technologies to traverse through the deep ice covering this ocean world, as well as instruments to assess habitability and to detect biomarkers. (Image credit: NASA/JPL-Caltech/SETI Institute)

PLANETARY EXPLORATION SCIENCE TECHNOLOGY OFFICE

PROJECT:
Planetary Exploration Science Technology Office (PESTO)

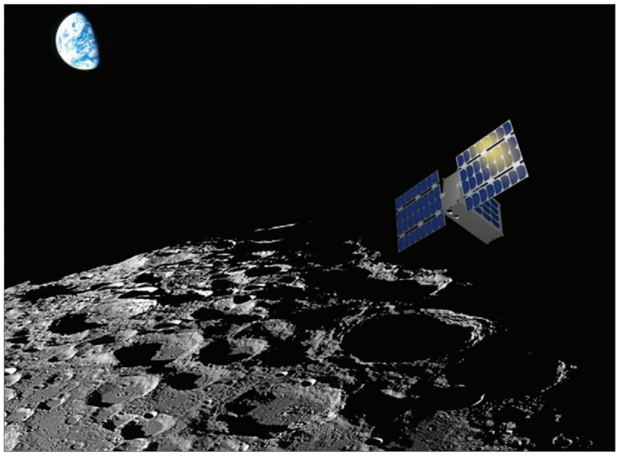
SPONSORING ORGANIZATION:
Planetary Science Division (PSD)

KEY POINTS:
A new office has been created to manage the development of scientific instruments, space vehicle technologies, and mission support technologies needed for future planetary science missions.

Planetary Science missions span the solar system and encompass the harshest known environments. From the scorching, caustic surface of Venus to the frigid cold-traps on the Moon, advanced technologies are needed to orbit, land, and explore all planetary bodies to seek answers to the fundamental science questions that guide NASA exploration: How did our solar system form and evolve? Is there life beyond Earth? And what are the hazards to life on Earth?

New capabilities are required to enable exciting planetary science missions across a very broad set of destinations. The 2011 Decadal Survey Visions and Voyages recommended that PSD set aside 6 – 8% of its budget each year to develop technologies needed for these future missions. Per the decadal survey, these technologies should encompass science instruments, technologies needed for solar system access and in situ exploration, and core supporting technologies such as trajectory analysis and autonomy. In addition, a Planetary Science Technology Review Panel (July 2011) recommended a similar budget and that a technology program director should be named and given responsibility for achieving these goals, with a supporting office.

Accordingly, in 2017 PSD chartered the Planetary Exploration Science Technology Office (PESTO) to manage non-nuclear planetary technology investments that are not yet specific to a mission in development. The PESTO office acts as an agent of NASA Headquarters and is managed and supported by staff at the Glenn Research Center with support from other institutions as appropriate. The key functions of the PESTO office are outlined on the following page.



PESTO develops technologies like the Miniature Neutron Spectrometer (Mini-NS)—a neutron detector funded by PSD's PICASSO program that will fly on the Lunar Polar Hydrogen Mapper (LunaH-Map) pictured above. The 6-unit LunaH-Map CubeSat will produce the most detailed map to date of the Moon's water deposits.

Strategy

Annually, PESTO recommends a technology strategy to PSD to establish technology investment priorities, define project goals and requirements, and define a schedule and approach to achieve them. PESTO conducts in-depth assessments and establishes design reference missions as needed to determine technology goals and measure technology benefits and relevance. PESTO has created a roadmap to develop the recommended technologies, quantifying technical goals and scoping cost and schedule.

Management

PESTO has established a management structure to manage technology elements under its purview. This management function includes writing solicitations, running panels, and recommending selections; monitoring technical work and tracking financials; synthesizing tasks to create system-level benefits; and recommending new work. PESTO coordinates with existing programs that are managing mission-specific technology development, where projects, budgets, and requirements are established outside of PESTO to support a flight mission.

Coordination

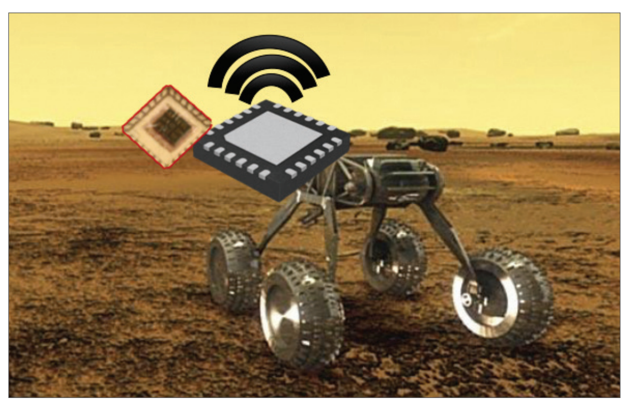
PESTO tracks investments in relevant work being done throughout the Agency, provides technical need statements to other organizations to help influence external investments as appropriate, and maintains awareness of relevant work in industry and academia and other government agencies.

Infusion

The goal of all technology development within PSD is to infuse new technologies into flight missions. PESTO fosters technology infusion by providing communication opportunities between technology developers and mission engineers, mission planners, and other stakeholders. PESTO is employing "infusion mentors" to bring people with flight experience together with technology developers sooner rather than later. In addition, PESTO is collecting and archiving technology infusion data to better understand obstacles and to make recommendations to improve PSD's technology programs.

> **Exciting new science discoveries of the future require investments in more capable technologies now—particularly in technologies that operate in extreme environments.**
>
> – Dr. Lori Glaze, PSD Director

For more information, visit the PESTO website: https://www1.grc.nasa.gov/space/planetary-exploration-science-technology-office-pesto/



PESTO is developing technologies for future exploration of the surface of Venus such as this robust radio transmitter chip being developed by Debbie Senesky at Stanford University. (Image credit: Geoff Landis/NASA GRC and Mina Rais-Zadeh/NASA JPL)

▶ Advances in autonomous technology may enable orbiters, aerial systems, and landed assets to work together without human intervention to explore distant worlds. Artist's conceptions from left to right: NASA's Mars Atmosphere and Volatile Evolution (MAVEN) mission, a balloon-borne sensor system, and NASA's Mars 2020 rover.

2018 WORKSHOP ON AUTONOMY FOR FUTURE NASA SCIENCE MISSIONS

PROJECT:
2018 Workshop on Autonomy for Future NASA Science Missions

SPONSORING ORGANIZATION:
SMD in collaboration with Carnegie Mellon University and the SETI Institute

KEY POINTS:
Over 85 technical leaders from industry, academia, and NASA convened to explore how autonomy can impact upcoming NASA missions. Work continued after the workshop, as teams refined and produced recommendations for how autonomy could affect various future mission types.

Imagine a team of small robots collaboratively exploring the surface of Mars without human intervention, looking for sources of water that could be used by future human explorers. Or how about a large telescope that robots assemble in space to identify distant Earth-like planets? Or a system of networked probes on the surface of Venus that detect a volcanic eruption, and notify orbital and aerial platforms to investigate the event's effects? These amazing missions all have one thing in common: they require autonomous systems to succeed.

Autonomy can enable remote systems to collect and evaluate data, make decisions, and take appropriate action—all without human input. Autonomous technologies can enable navigation, hazard detection, fault detection, and mission planning; they can even allow systems to learn when things go wrong. But NASA needs to determine which autonomous technologies it should invest in to meet the Agency's science objectives.

In October 2018, NASA SMD convened the 2018 Workshop on Autonomy for Future Science Missions to explore this issue and gather information to inform Agency decisions. Goals of the workshop included:

1) Identification of emerging autonomy technologies becoming viable in the next 10-15 years that could:

- Enable or enhance mission capabilities
- Reduce mission risk
- Reduce mission cost

2) Identification of potential collaboration and partnership opportunities with industry and/or academia that will enable these technologies

Over 85 key technical leaders from industry, academia, and NASA convened at Carnegie Mellon University to explore how autonomy can impact upcoming NASA missions. Keynote speakers highlighted the latest autonomy research and development efforts and reflected on how these technologies could transform NASA missions.

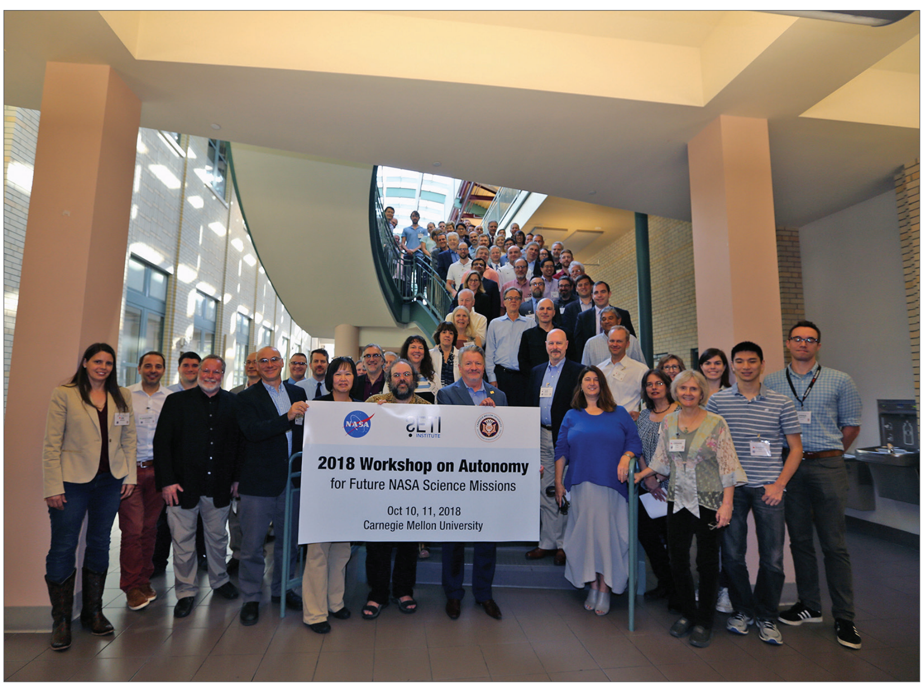
Panel discussions featuring experts from industry, academia, and NASA explored how to foster collaboration between NASA and industry/academia and reviewed panel members' experiences (e.g., successes, problems encountered, and lessons learned) with autonomous systems that are employed today.

NASA also invited a number of graduate students from relevant fields of study to participate in the workshop and present brief "lightning talks" and posters on their research efforts.

Workshop attendees also participated in smaller "breakout" discussions to determine how advanced autonomy could impact particular design reference missions (DRM) including Earth, Small Bodies, Lunar, Heliophysics, Venus, Mars, Ocean Worlds, and Astrophysics missions. These smaller DRM groups also worked to identify gaps between NASA's technology development efforts and those of industry/academia and proposed methods to infuse beneficial technologies into NASA missions. At the end of the two-day workshop, each DRM team presented its preliminary findings to the larger group.

After the workshop, the DRM teams continued to refine their analyses. Each team produced a report that defines the DRM in detail, details the autonomy technologies required to make such missions a reality, and recommends SMD actions.

More information, including video presentations, slides from the workshop, and speaker profiles, is available online at: https://science.nasa.gov/technology/2018-autonomy-workshop. A workshop summary including the follow-on DRM team reports will be available at this site, as well.



▶ Participants at the 2018 Workshop on Autonomy for Future NASA Science Missions.

APPENDIX: THE SMD TECHNOLOGY DEVELOPMENT STRATEGY

Sustained investment in technology development—as well as infusion of viable new technologies—are key to NASA's success. The Agency's airborne and in-space flight missions, along with its scientific research and analysis (R&A) programs, represent the primary customer base for SMD's technology development efforts. SMD's approach is to mature enabling technologies years in advance of mission implementation, thereby retiring risk, reducing cost, and increasing the likelihood that new technologies will be incorporated into flight projects.

SMD aligns its technology investment strategy with the Agency's overarching approach, which is described in detail in the NASA Strategic Technology Investment Plan (STIP)[1]. The Agency has developed a comprehensive set of roadmaps[2] that correspond to 15 different technology areas. Within these areas are hundreds of detailed taxonomies that map directly to current NASA projects or to potential future investments. As described in the STIP, each of these elements has been placed into one of three categories: "Mission Critical," which are technologies that are required for planned or proposed missions; "Mission Enhancing," which are technologies that significantly improve mission performance; and "Transformational," which are revolutionary "over-the-horizon" technologies for missions yet to be conceived.

The Agency strives to achieve a balanced portfolio of 70%-20%-10% between Mission Critical, Mission Enhancing, and Transformational technologies, respectively, and the technology programs of SMD and the Space Technology Mission Directorate (STMD) strive to meet these goals. STMD is an important SMD partner in this process, particularly for technology development efforts that are applicable Agency-wide. SMD refers to the Mission Critical and Mission Enhancing categories as "Mission Pull," while the Transformational category is described as "Push." The pyramid figure on the following page roughly depicts the alignment of SMD and STMD technology programs.

SMD strives to invest in technologies that support the needs of its four science divisions. Effective technology development requires careful analysis of technology gaps, identification of technologies to fill those gaps, sustained investment to advance the chosen technologies, and successful infusion into missions or other products. SMD divisions receive guidance from the National Academies' decadal surveys and the science community—as well as direction from the Agency—which they carefully consider as they develop strategic science plans.

Based on the science requirements identified in these plans, each division determines the technology gaps that must be filled. Typically, these gaps concern a

DEFINITIONS OF NASA TECHNOLOGY READINESS LEVELS (TRL)[3]

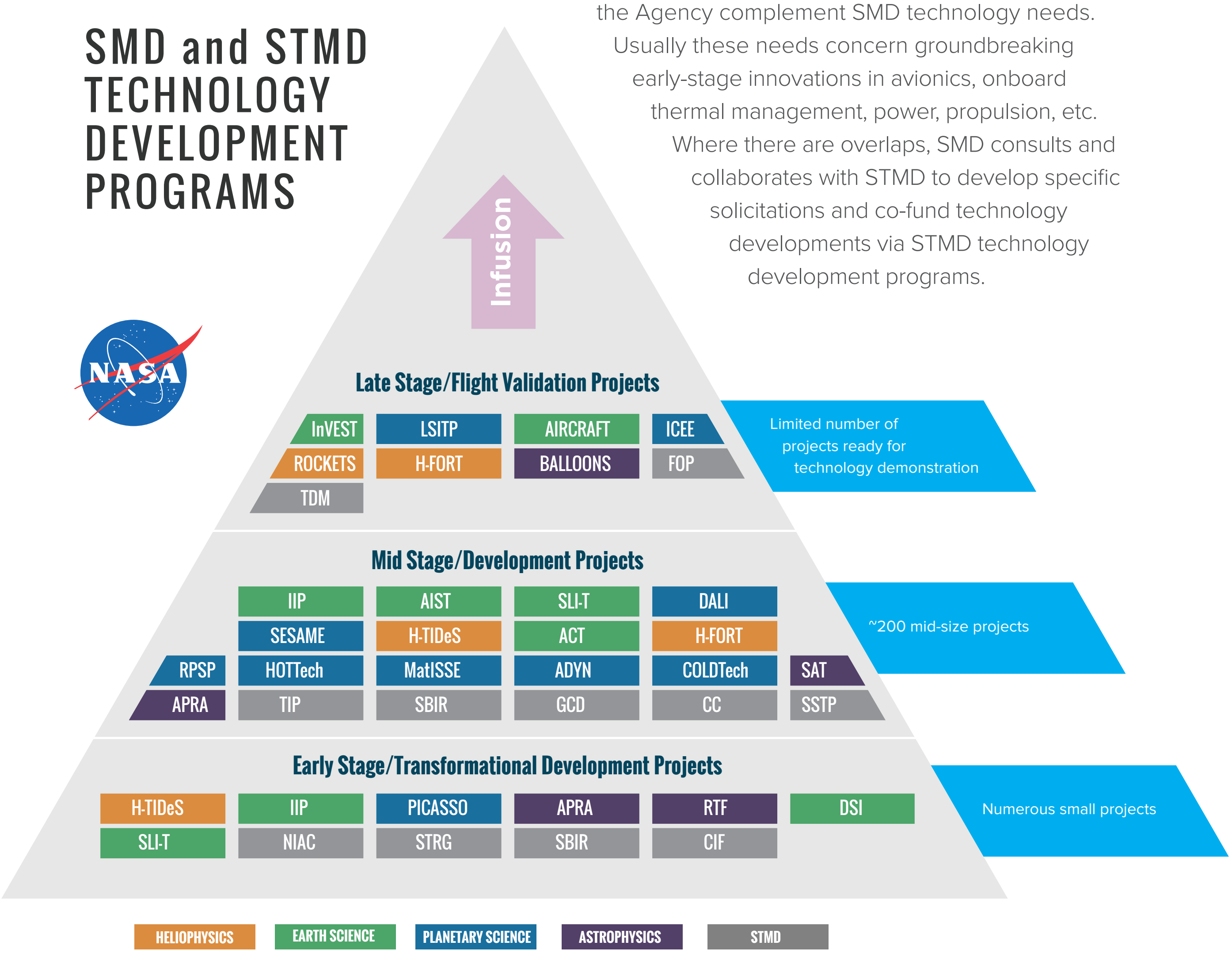
	DEFINITION
1	Basic principles observed and reported.
2	Technology concept and/or application formulated.
3	Analytical and experimental critical funtion and/or characteristic proof of concept.
4	Component and/or breadboard validation in laboratory environment.
5	Component and/or breadboard validation in relevant environment.
6	System/sub-system model or prototype demonstration in a relevant environment.
7	System prototype demonstration in an operational environment.
8	Actual system completed and "flight qualified" through test and demonstration.
9	Actual system flight proven through successful mission operations.

[1] The NASA Strategic Technology Investment Plan 2017 is available online at https://www.nasa.gov/offices/oct/home/sstip.html.
[2] The 2015 NASA Technology Roadmaps are available online at https://www.nasa.gov/offices/oct/home/roadmaps/index.html.
[3] NPR 7123.1B, NASA Systems Engineering Processes and Requirements (available online at https://nodis3.gsfc.nasa.gov)

need for instruments or space platforms with new or increased capabilities. Each SMD division accomplishes its technology development via competed opportunities offered through low- to mid-stage technology development programs (typically for technologies at TRLs 1-6) or via later-stage directed or competed flight programs (typically for technologies at TRLs 7-9). SMD divisions establish their own technology development programs to actively manage technology development efforts that are implemented outside of flight programs, thus ensuring progress and value are achieved for the directorate's investments. SMD's competed opportunities vary; some request ideas for development, while others are in response to a specific set of division requirements. However, all competed technology development opportunities within SMD employ a peer review process to determine the optimal investment strategies.

The SMD Chief Technologist also reviews the Agency technology roadmaps to determine if any of the technology needs identified elsewhere in the Agency complement SMD technology needs. Usually these needs concern groundbreaking early-stage innovations in avionics, onboard thermal management, power, propulsion, etc. Where there are overlaps, SMD consults and collaborates with STMD to develop specific solicitations and co-fund technology developments via STMD technology development programs.

SMD and STMD TECHNOLOGY DEVELOPMENT PROGRAMS



STMD PROGRAMS (FY18)

CC Centennial Challenges
CIF Center Innovation Fund
FOP Flight Opportunities Program
GCD Game Changing Development
NIAC NASA Innovative Advanced Concepts
SBIR Small Business Innovation Research
SSTP Small Spacecraft Technology Program
STRG Space Technology Research Grants
TDM Technology Demonstration Mission
TIP Tipping Point

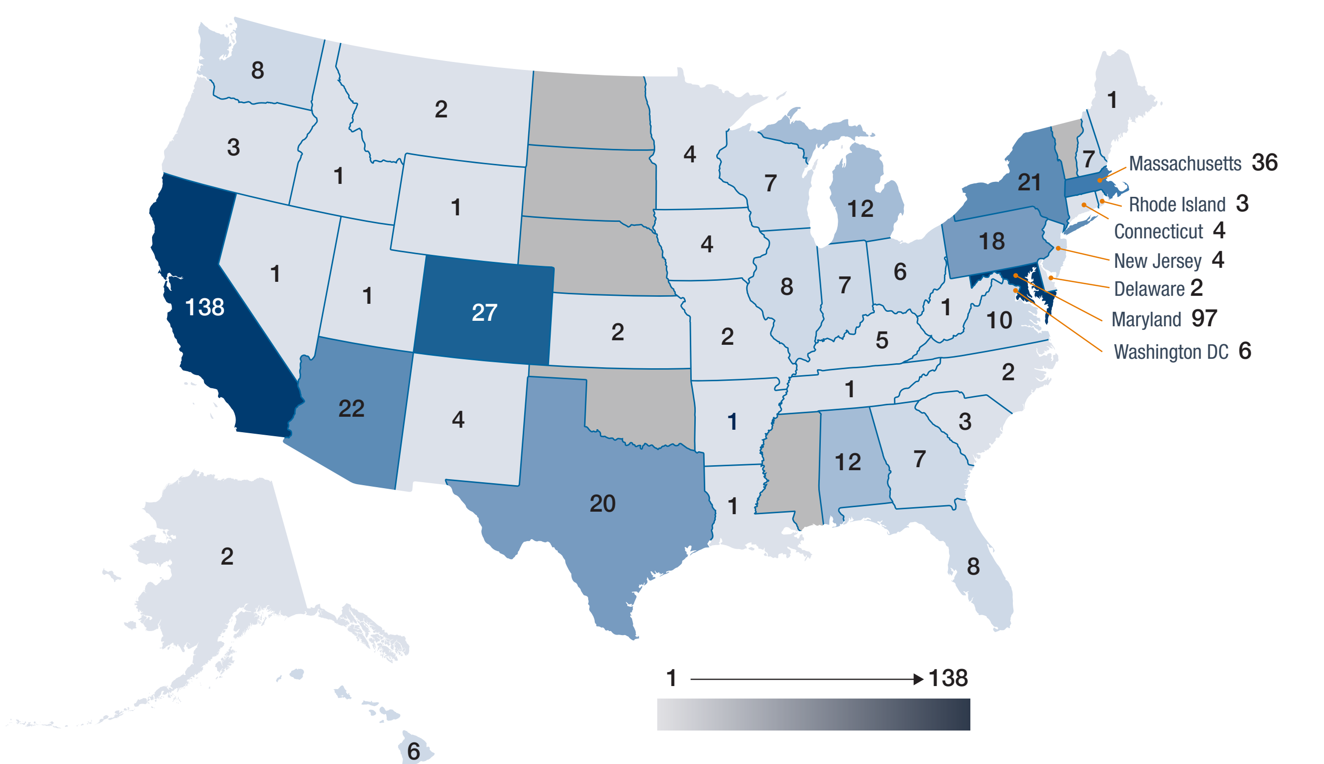
▶ SMD and STMD strategic technology development programs facilitate NASA's groundbreaking science achievements and enable the Agency to meet its goals. (See the table on pages 2-3 for a description of SMD division technology development programs)

Leveraging STMD's crosscutting technology developments and STMD support of nascent, highly innovative concepts has resulted in a more strategically balanced technology portfolio for SMD and has enabled SMD technology programs to better focus on mid-stage and later-stage technology development.

SMD applies this robust process to mature technologies to an advanced TRL such that they can be applied in a flight mission or scientific research and analysis project. Many key technologies undergo independent technology readiness assessments during the development process. If a development effort achieves TRL 6, the technology may be targeted for infusion into an SMD flight program. Prior to infusion, appropriate technologies may first be tested in a flight environment on a suborbital platform (aircraft, rocket, or balloon). Once a technology is infused into a flight program, that program is responsible for refining the technology so that it can be used for the specific mission application.

SMD also accomplishes technology development by establishing partnerships with other government agencies, higher education institutions, and industry. The directorate also funds student fellowship programs that contribute to technology development such as the Nancy Grace Roman Technology Fellowship and NASA Earth and Space Science Fellowship (NESSF). In addition, SMD leverages technology development efforts sponsored through research and development funds at the NASA centers.

The SMD Chief Technologist works with the SMD senior leadership team to coordinate the development and utilization of technology across the entire directorate. The SMD Chief Technologist is also the directorate's primary interface to STMD; to other NASA organizations responsible for technology development, such as the Office of the Chief Engineer (OCE); and to entities external to the Agency that also develop advanced technologies, such as other domestic agencies, foreign space agencies, industry, and academia.



▶ Locations of Principal Investigators for SMD technology development projects active in 2018.

ACRONYMS

AC	Alternating-Current
ACRE	Agronomy Center for Research and Education
ACT	Advanced Component Technologies
AIST	Advanced Information Systems Technology
ALD	Atomic Layer Deposited
APL	Applied Physics Laboratory
APRA	Astrophysics Research and Analysis
ATHENA	Advanced Telescope for High ENergy Astrophysics
BSM	Baseband Spectrometer Module
CETUS	Cosmic Evolution Through UV Spectroscopy
CGI	Coronagraph Instrument
COR	Cosmic Origins Program
CRM	Cloud resolving model
CSU	Colorado State University
CSV	Comma Separated Values
DALI	Development and Advancement of Lunar Instrumentation
DASS	Data Analytics and Storage System
DBE	Digital Back End
DC	Direct-Current
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German space agency)
DRM	Design Reference Missions
DRPS	Dynamic Radioisotope Power Systems
DST	Decadal Survey Testbed
ESA	European Space Agency
ESTO	Earth Science Technology Office
FOXSI	Focusing Optics X-ray Solar Imager
GCE	Goddard Cumulus Ensemble
GCI	Grand Challenge Initiative

GDC	Geospace Dynamics Constellation
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GRC	Glenn Research Center
GSFC	Goddard Space Flight Center
H-FORT	Heliophysics Flight Opportunities for Research and Technology
H-TIDeS	Heliophysics Technology and Instrument Development for Science
HDFS	Hadoop Distributed File System
HEMT	High-Electron-Mobility Transistor
IC	Integrated Circuit
ICI-5	Investigation of Cusp Irregularities-5
IDL	Interface Definition Language
IIP	Instrument Incubator Program
IMAP	Interstellar Mapping and Acceleration Probe
IR	Infrared
ISS	International Space Station
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
LISA	Laser Interferometer Space Antenna
LLISSE	Long-Lived In-Situ Solar System Explorer
LNFE	Low Noise Front End
LO	Local Oscillator
LSITP	Lunar Surface Instrument and Technology Payloads
LUMOS	LUVOIR Ultraviolet Multi-Object Spectrograph
LUVOIR	Large Ultraviolet/Optical/Infrared Surveyor

MAVEN	Mars Atmosphere and Volatile Evolution
MCP	Microchannel Plate
MEDICI	Magnetosphere Energetics, Dynamics, and Ionospheric Coupling Investigation
MEM	Microwave Electrojet Magnetogram
MO	Master Oscillator
MOPA	Master Oscillator Power Amplifier
MOSFET	Metal-oxide Semiconductor Field-effect Transistor
NCCS	NASA Center for Climate Simulation
NESSF	NASA Earth and Space Science Fellowship
NIST	National Institute of Standards and Technology
NOAA	National Oceanic and Atmospheric Administration
NPLP	NASA Provided Lunar Payloads
NU-WRF	NASA-Unified Weather Research and Forecasting
NVCT	Nanoscale Vacuum Channel Transistor
OCE	Office of the Chief Engineer
PA	Power Amplifier
PCOS	Physics of the Cosmos
PESTO	Planetary Exploration Science Technology Office
PI	Principal Investigator
PICASSO	Planetary Instrument Concepts for the Advancements of Solar System Observations
PMC	Polar Mesospheric Cloud
PSD	Planetary Science Division
R&A	Research and Analysis
RAM	Random Access Memory
RFI	Radio-Frequency Interference

RPM	Revolutions per Minute
RPS	Radioisotope Power Systems
RPSP	Radioisotope Power System Program
RTF	Roman Technology Fellowships
RZSM	Root Zone Soil Moisture
SAT	Strategic Astrophysics Technology
SBC	Single Board Computer
SCL	Super Cloud Library
SESAME	Scientific Exploration Subsurface Access Mechanism for Europa
SLI-T	Sustainable Land Imaging Technology
SMD	Science Mission Directorate
SNoOPI	SigNals of Opportunity: P-band Investigation
SoOp-AD	Signals of Opportunity Airborne Demonstration
SRON	Netherlands Institute for Space Research
STIP	Strategic Technology Investment Plan
STMD	Space Technology Mission Directorate
SUDA	SUrface Dust Analyzer
SWE	Snow Water Equivalent
TDC	Technology Demonstration Convertor
TEMPEST-D	Temporal Experiment for Storms and Tropical Systems Demonstration
TES	Transition-Edge Sensor
TRL	Technology Readiness Level
UV	Ultraviolet
WFIRST	Wide Field Infrared Survey Telescope
X-IFU	X-ray Integral Field Unit
XS	Cross strip

National Aeronautics and Space Administration

NASA Headquarters

300 E Street SW

Washington, DC 20564

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