

National Aeronautics  
and Space Administration



SCIENCE MISSION DIRECTORATE

# TECHNOLOGY HIGHLIGHTS 2016



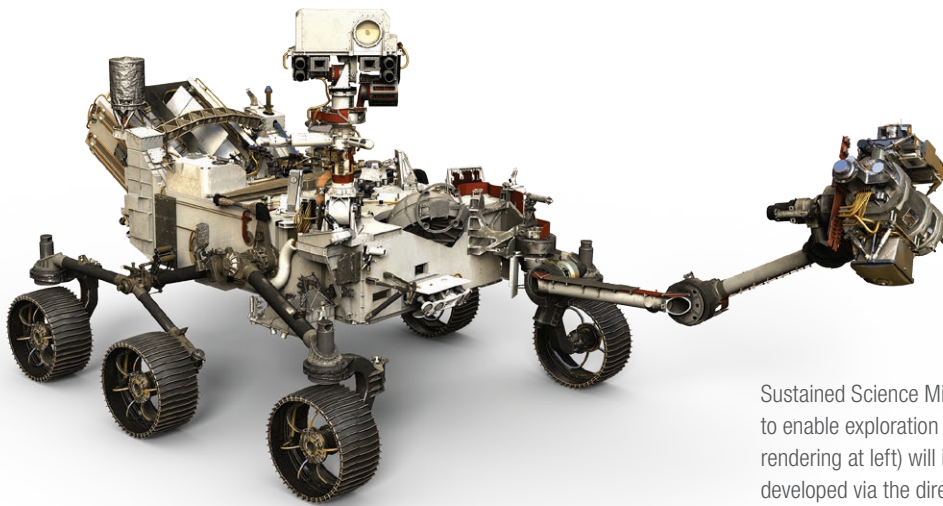
Enabling groundbreaking  
science through  
technological innovation...





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# INTRODUCTION



Sustained Science Mission Directorate technology investment is helping to enable exploration of the Red Planet. NASA's Mars 2020 rover (artist's rendering at left) will include three new instruments featuring technologies developed via the directorate's technology programs.

## SMD BY THE NUMBERS



**Spacecraft**  
105 missions\*  
88 spacecraft



**CubeSats**  
12 science missions\*  
11 technology demonstrations



**Balloon Payloads**  
13 science payloads  
13 piggyback/student payloads



**Sounding Rocket Flights**  
14 science missions  
3 technology/student missions



**Earth-Based Investigations**  
25 major airborne missions  
8 global networks



**Technology Development**  
325 active projects in 2016



**Research**  
10,000+ U.S. scientists funded  
3,000+ competitively selected awards

\*117 space-based missions

As a leading National scientific research agency, NASA sponsors numerous cutting-edge research programs and complementary missions designed to expand our scientific knowledge and understanding of the universe, the solar system, and Earth. The Science Mission Directorate (SMD) enables NASA to achieve its science goals in the context of the National science agenda. Whether probing the sun's coronal regions, investigating the nature of black holes, exploring the surface of Mars, or monitoring climate change on Earth, SMD missions are enabling groundbreaking science. Accomplishing this breakthrough science, however, often requires significant technological innovation—e.g., instruments

or platforms with capabilities beyond the current state of the art. SMD's targeted technology investments fill these gaps, enabling NASA to build the challenging and complex missions needed to fulfill the Agency's scientific goals. The directorate works to ensure that NASA actively identifies and invests in the right technologies at the right time to enable the Agency's science program.

SMD's strategic decisions regarding future missions and scientific pursuits are guided by Agency goals, input from the science community—including the recommendations set forth in the decadal surveys produced by the National Academies of Science,

Engineering and Medicine—and a commitment to maintain a balanced program across the major science disciplines. Toward this end, each of the four SMD science divisions— Astrophysics, Earth Science, Heliophysics, and Planetary Science—develops a targeted science program, along with a corresponding set of missions designed to gather the required data.

## NASA TECHNOLOGY READINESS LEVEL (TRL) DEFINITIONS

Source: NPR 7123.1B, NASA Systems Engineering Processes and Requirements.

NASA TRL	DEFINITION
1	Basic principles observed and reported.
2	Technology concept and/or application formulated.
3	Analytical and experimental critical function 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.

SMD technology development supports these division science programs, and is part of a comprehensive Agency-wide strategy that involves coordination with the NASA Chief Technologist and other Agency mission directorates. This coordination helps ensure that crosscutting technology development needs are identified across the Agency and that there is optimal return on investments to fulfill those needs.

SMD accomplishes technology development through technology programs established in each of its four science divisions. (See the table on the next page for a list of SMD technology development programs.) If a technology development effort reaches a NASA Technology Readiness Level (TRL) that is high enough, it may be infused into an SMD flight program and targeted for further maturation, enabling its use for a specific mission application. In some cases, other programs within SMD (e.g., the Astrophysics Division’s Scientific Balloon Program and the Planetary Science Division’s Mars Exploration Program) sponsor technology development related to specific program objectives.

This report highlights the most significant SMD technology development efforts of 2016. Chapter two highlights technology achievements that were sponsored by SMD technology development programs in 2016. The third chapter describes highlights from recent SMD technology infusions—SMD-sponsored technologies that have been transferred to the technology user (typically a flight mission) for refinement and eventual application. Appendix A briefly reviews the strategy SMD employs to ensure the directorate’s technology needs are fulfilled, including the coordination between SMD and the NASA Space Technology Mission Directorate.



## SMD TECHNOLOGY DEVELOPMENT PROGRAMS

### EARTH SCIENCE DIVISION (FUNDED AND MANAGED THROUGH THE EARTH SCIENCE TECHNOLOGY OFFICE, ESTO)

<b>Advanced Component Technologies (ACT)</b>	Develops a broad array of components and subsystems for instruments and observing systems.
<b>Instrument Incubator Program (IIP)</b>	Funds innovative technologies leading directly to new Earth observing instruments, sensors and systems.
<b>Advanced Information Systems Technology (AIST)</b>	Develops tools and techniques to acquire, process, access, visualize, and otherwise communicate Earth science data.
<b>In-Space Validation of Earth Science Technologies (InVEST)</b>	Enables on-orbit technology validation and risk reduction for small instruments and instrument systems that could not otherwise be fully tested on the ground or airborne systems.

### HELIOPHYSICS DIVISION

<b>Sounding Rocket Program Office</b>	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.
<b>Heliophysics Technology and Instrument Development for Science (H-TIDeS)</b>	Supports basic research of new technologies and feasibility demonstrations that may enable future science missions. Also supports science investigations through suborbital flights that often involve a significant level of technology development.

### PLANETARY SCIENCE DIVISION (PSD)

<b>Planetary Instrument Concepts for the Advancements of Solar System Observations (PICASSO)</b>	Funds the development of low-TRL technologies (TRL 1-4) leading directly to the development of new Planetary Science observing instruments, sensors and in situ systems.
<b>Maturation of Instruments for Solar System Exploration (MatISSE)</b>	Matures innovative instruments, sensors, and in situ system technologies (TRL 3-6) to the point where they can be successfully infused into new Planetary Science missions.
<b>Homesteader</b>	Advances Planetary Science technologies in advance of New Frontiers Announcements of Opportunities.
<b>Planetary Science and Technology through Analog Research (PSTAR)</b>	Provides instrument technology development coupled with systems-level field tests.
<b>Radioisotope Power System Program (RPSP)</b>	Strategically invests in nuclear power technologies to maintain NASA's current space science capabilities and enable future space exploration missions.

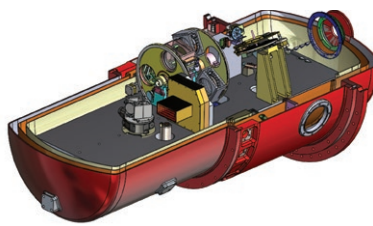
### ASTROPHYSICS DIVISION

<b>Astrophysics Research and Analysis (APRA)</b>	Supports basic research of new technologies (TRL 1-3) and feasibility demonstrations that may enable future science missions. Also supports science investigations through suborbital flights that often involve a significant level of technology development.
<b>Strategic Astrophysics Technology (SAT)</b>	Develops mid-TRL technologies (TRL 3-6). Each focused Astrophysics program manages an SAT element separate from flight projects: Technology Development for Physics of the Cosmos (TPCOS), Technology Development for Cosmic Origins Program (TCOR), and Technology Development for Exo-Planet Missions (TDEM).
<b>Roman Technology Fellowships</b>	Provides opportunities for early-career astrophysics technologists to develop the skills necessary to lead astrophysics flight instrumentation development projects, and fosters career development by providing incentives to help achieve long-term positions. Develops innovative technologies that enable or enhance future astrophysics missions.



# TECHNOLOGY DEVELOPMENT

## HIRMES: A NEW HIGH-RESOLUTION MID-IR INFRARED SPECTROMETER FOR SOFIA



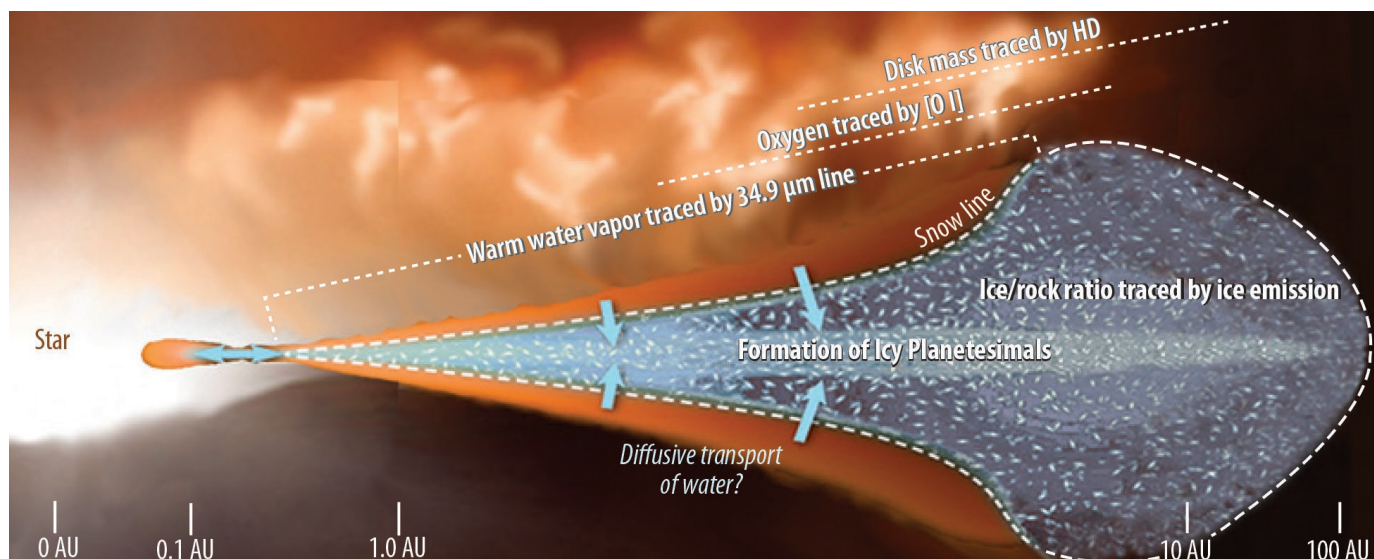
Cutaway CAD model representation of proposed HIRMES instrument design. (Credit: GSFC HIRMES Instrument Team)

**Technology Development:** NASA is developing a new instrument to expand the boundaries of astronomy research. A team of scientists and technologists at NASA's Goddard Space Flight Center

(GSFC) is developing the High-Resolution Mid-Infrared Spectrometer (HIRMES)—an innovative instrument that will enable new scientific investigations and important contributions to our understanding of the cosmos. HIRMES commissioning is anticipated for late 2018 on NASA's Stratospheric Observatory for Infrared Astronomy (SOFIA), a heavily modified Boeing

747SP that carries a 2.5m-diameter infrared telescope. SOFIA flies above ~95% of the Earth's atmospheric water vapor, allowing astronomers to gain access to wavelengths that are not possible to observe from the ground, even with the most powerful ground-based telescopes. HIRMES applies emerging detector and optical technologies tailored to take maximum advantage of the unique platform provided by SOFIA, covering the 25–122-micron spectral range with resolving powers ranging from 600 to 100,000.

HIRMES will extend proven technologies, striking a balance between pushing the state of the art and providing reliable performance to SOFIA's growing user community. HIRMES will employ superconducting transition edge sensor (TES)-based bolometers, operating at temperatures of ~0.1 K to provide sensitivity limited only by the intrinsic signal-to-noise ratio imposed by the sky background. These detectors promise an order of magnitude lower noise compared



HIRMES on SOFIA will probe the structure and evolution of protoplanetary disks and increase our ability to model these systems as they evolve to fledgling planetary systems. (Credit: GSFC HIRMES Instrument Team)

with the heterodyne detectors presently deployed in SOFIA instrumentation, and will decrease observing time by a factor of ~200 on spectral lines of interest. HIRMES detectors will be arrayed in a 16x64-element format to provide low- and medium-resolution spectroscopic observations, including an imaging capability. A separate 8x16-element array optimized for low backgrounds will be used for high-resolving power observations. A multi-stage refrigeration system will provide the ~100mK heat sink needed for background-limited detector performance. Optical dispersion of the light delivered by the telescope will be accomplished via a system of gratings, mirrors, and tunable Fabry-Perot interferometric monochromators.

**Impact:** HIRMES' prime investigation is a detailed study of the processes leading to the formation of planetary systems over a spectral range rich in ionic, atomic, and molecular lines. The HIRMES science program will determine the structure and evolution of protoplanetary disks and will increase our ability to model these systems as they evolve from homogeneous disks to fledgling planetary systems. At the beginning of their lives, stars significantly interact with their environments and the HIRMES program will advance our understanding about the ways these interactions regulate star formation. The HIRMES team will also study the formation processes of massive protostars and the mechanisms that accelerate dust in asymptotic giant branch (AGB) stars. NASA anticipates significant demand within the scientific community for the powerful new capabilities that HIRMES will provide.

**Status and Future Plans:** The GSFC team developed an instrument concept study in 2016, leading to the competitive selection of HIRMES for development. Work began immediately on development of the instrument, including laboratory evaluation of brass-board subsystems and procurement of limited long-lead hardware items to support an aggressive development schedule. The HIRMES team is working toward a critical design review in FY17, followed by hardware development to enable instrument delivery in late 2018.

**Sponsoring Organization:** HIRMES development is sponsored by the SMD Astrophysics Division in conjunction with the SOFIA Program Office. Dr. Harvey

Moseley is the HIRMES Principal Investigator, with GSFC as the lead NASA Center for HIRMES development. SOFIA is managed by NASA's Ames Research Center and operated out of NASA's Armstrong Flight Research Center in Palmdale, California.

## RAVAN CUBESAT TO DEMONSTRATE NEW TECHNOLOGY FOR RADIATION BALANCE MEASUREMENTS

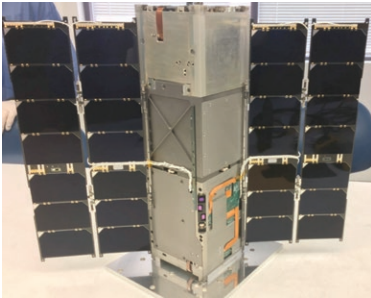


RAVAN was one of seven CubeSats aboard the Atlas V rocket that carried the WorldView-4 satellite into orbit. (Credit: United Launch Alliance/Lockheed Martin)

### Technology

**Development:** The Radiometer Assessment using Vertically Aligned Nanotubes (RAVAN) CubeSat mission launched on November 11, 2016 as a secondary payload on a United Launch Alliance Atlas V rocket from Vandenberg Air Force Base. RAVAN will demonstrate that accurate and critically needed Earth climate measurements can be made with a small instrument, thanks in part to new carbon

nanotube technology that absorbs light extremely efficiently. RAVAN features small, accurate radiometers to measure the strength of the Earth's total outgoing radiation across the entire spectrum of energy, from the ultraviolet to the far infrared. Vertically aligned carbon nanotubes (VACNT) serve as the radiometer's light absorber and will enable the radiometer to gather nearly the full spectrum of light reflected and emitted from Earth. The RAVAN team will study Earth's radiation imbalance, which is the difference between the amount of energy from the sun that reaches the Earth and the amount that is reflected or radiated back into space. While thought to be less than one percent, the imbalance is known to be essential for understanding and predicting changes in the planet's climate.



A model of the RAVAN spacecraft with fully deployed solar panels. (Credit: JHU APL)

**Impact:** RAVAN could eventually lead the way to a constellation of miniature radiometers. Such a constellation could enable global coverage of Earth's radiation budget; provide diurnal sampling of rapidly varying phenomena

like clouds, plant life, ozone, and aerosols; and answer longstanding questions about the Earth's climate.

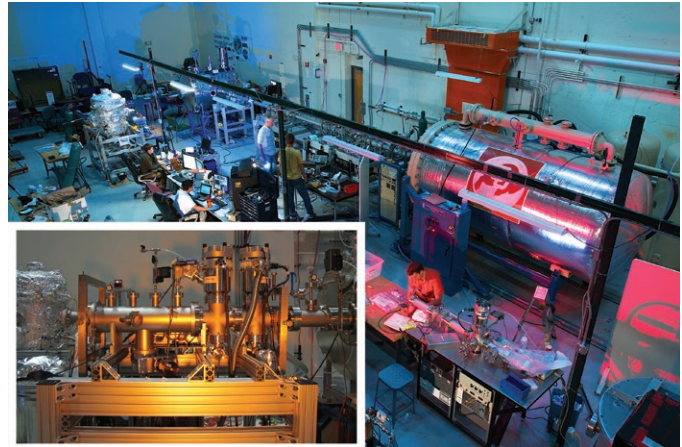
**Status and Future Plans:** Two-way communication has been established with the CubeSat. Once the spacecraft is fully commissioned, the payload will be powered on and demonstrations will begin. RAVAN's flight is expected to last up to one year.

**Sponsoring Organization:** PI William Swartz led development of RAVAN at Johns Hopkins Applied Physics Lab, with funding from the Earth Science Division's InVEST program.

## NEW FACILITY ENABLES THE STUDY OF SHOOTING STARS IN THE LABORATORY

**Technology Development:** In the last three years, a NASA-sponsored team at the University of Colorado has developed a facility that allows "shooting stars" to be generated in laboratory conditions. The heart of this unique capability is a three-million-Volt electrostatic accelerator that is capable of accelerating small dust particles to velocities from 10-70 km/s—roughly the range at which micrometeoroids enter Earth's atmosphere and become "shooting stars." While some micrometeoroids are visible to the naked eye, most are observable only by sensitive instruments such as radars. Researchers use this new facility to learn about the behavior of different types of accelerated dust particles so that scientists can better interpret measurements made in the field. In the laboratory, the accelerated particles are introduced into a chamber with elevated gas pressure, where they are heated rapidly through collisions with molecules. The heat causes some or all of the particle material to wear away—a process called ablation. Sensitive electronic and optical sensors in the chamber detect the amount of ionization generated and the light emitted along

the path of the ablating particles, allowing researchers insight into the process.



Back: The dust accelerator facility operated at the University of Colorado. Front: The setup where the ablation of dust particles is studied. (Credit: IMPACT Institute)

**Impact:** This new facility provides information about how dust particles made of varying materials undergo an elementary process that occurs in unique conditions that are difficult to simulate. The experimental data generated by this facility are being used to improve the interpretation of meteor radar observations, with the goal of resolving the total mass input and the origin of the extraterrestrial material entering Earth's atmosphere.

**Status and Future Plans:** In 2016, the research team extended the facility to include the capability to spatially-resolve optical observations, which provides critical information about the particles' deceleration during ablation. The team also successfully developed and tested new dust samples consisting of more complex mineral (or rocky) materials for acceleration in the facility. Currently, the research team is working on using these new samples to simulate differential ablation, where the more volatile elements evaporate first from the particle, followed by the more refractory elements. The differential ablation of meteoroids is responsible for the metallic layers observed in Earth's upper atmosphere, and characterizing this process in the laboratory will enable better understanding of observed data.

**Sponsoring Organization:** SMD's Heliophysics Division sponsors development of the ablation facility through the H-TIDeS program, with Prof. Zoltan Sternovsky as the PI. The dust accelerator is operated by the IMPACT Institute (Institute for Modeling Plasma, Atmospheres

and Cosmic Dust), a member of NASA's Solar System Exploration Research Virtual Institute (SSERVI), which is supported both by SMD and the Human Exploration and Operations Mission Directorate.

## NEW METHOD TO REMOTELY SENSE ICE SHEET SUBSURFACE TEMPERATURE DEMONSTRATED



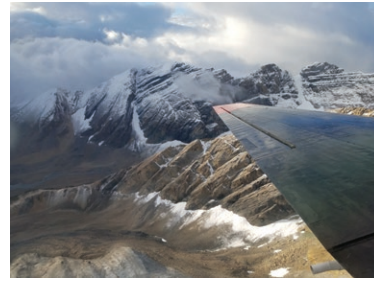
UWBRAD instrument installed in the DC-3T aircraft. The cylinder in the foreground is the deployable "periscope" antenna, and the instrument electronics are housed in the rack in the background. (Credit: Joel Johnson/OSU)

### Technology

**Development:** A new instrument, the Ultrawideband Software-Defined Microwave Radiometer (UWBRAD), aims to provide measurements of ice sheet thermal emission to remotely sense internal ice sheet temperature information. Physical temperature plays an important role in influencing stress-strain relationships in the ice sheet volume, and therefore impacts ice sheet dynamics

including deformation and flow across the ice sheet base. Previous studies and models have shown the potential of multi-frequency brightness temperature measurements to obtain deep ice sheet temperature information, given assumed ice sheet internal temperatures, electromagnetic permittivity, and other physical parameters such as density and particle grain size. UWBRAD is designed to provide brightness temperature observations over the 0.5-2 GHz range, using multiple frequency channels and full-bandwidth sampling of each channel.

In November 2015, the UWBRAD team successfully demonstrated a four-channel prototype of the UWBRAD on a tower in Antarctica. This ground-based test successfully demonstrated that lower frequencies can sense internal ice sheet temperatures at depths of several kilometers and showed warmer temperatures with increasing depth. In 2016, the UWBRAD team



A view of the Canadian Rockies near the Columbia Icefield during the September 5, 2016 flight test. (Credit: Joel Johnson/OSU)

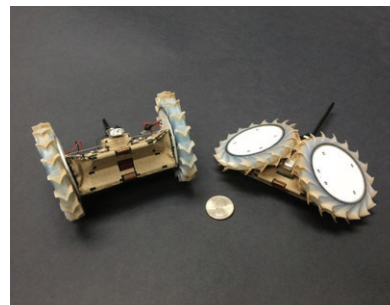
applied the lessons learned from this previous ground-based prototype demonstration to a full 12-channel airborne instrument, which had its first test flights in September 2016 onboard a Kenn Borek Airlines DC-3T aircraft over Greenland and parts of Canada.

**Impact:** No methods currently exist for remotely sensing ice sheet internal temperatures; presently, the only measured information is obtained from a small number of deep ice core sites. As an airborne instrument, UWBRAD could obtain this type of data over wide areas.

**Status and Future Plans:** The 2016 airborne tests provided approximately 10 hours of the first ultra-wideband microwave radiometer measurements of geophysical scenes including ice sheets. The UWBRAD project team intends to conduct additional flights to collect science data in early 2017.

**Sponsoring Organization:** NASA's Earth Science Division sponsors development of UWBRAD via the IIP. The PI is Joel Johnson of Ohio State University (OSU).

## POP-UP ROBOTS ENABLE EXTREME TERRAIN SCIENCE



PUFFER prototypes shown deployed (left) and folded (right). U.S. quarter shown for scale.

### Technology

**Development:** A NASA-led team is designing an extremely compact origami rover for new extreme terrain applications in both the planetary and Earth science domains. PUFFERS

(Pop-Up Flat Folding Explorer Robots) utilize a folding printed circuit board (PCB) as the rover chassis, which enables the platform to fold into a miniscule, palm-sized

volume. With this feature, many PUFFERs can be integrated into future spacecraft or packed into Earth science experiments at low cost. The multitude of PUFFERs would then be used to carry out science investigations that specifically require a distributed, multi-unit approach, such as entering cave formations on Mars or conducting spatially-distributed topographic mapping of ice on Earth. In addition to small packing volume, PUFFER's folding chassis provides unique mobility benefits; PUFFERs can collapse into a low-profile "crouch" to crawl beneath tight terrain features, such as overhung rocks, and to lower their center of gravity for ascending steep inclines. The highly-flexible origami-inspired chassis also provides impact-absorbing capabilities, allowing PUFFER to survive great falls.



PUFFER prototype collapsing to drive beneath a natural overhang during field testing in the Mojave Desert.

**Impact:** The PUFFER technology will provide low-cost access to new science-rich terrains both on Earth and beyond. Here on Earth, scientists hope to deploy swarms of PUFFERs to track ice fluctuations in the polar regions. Teams of researchers could deploy PUFFERs over ice sheets of interest from the air, dropping the impact-resistant rovers from helicopters. The PUFFERs would then remain behind and autonomously rove over the ice while making measurements. The units would recharge themselves using solar energy, allowing them to operate for months and possibly years at a time. Work is currently underway to develop and test PUFFERs for snow and ice mobility, and the prototypes were recently tested at Mt. Erebus in Antarctica. Beyond our own planet, PUFFERs will provide future NASA missions with a low-cost add-on technology for accessing new extreme terrains. A swarm of PUFFERs could be folded up into a parent spacecraft, such as a larger rover or lander, and then be deployed into terrain features

that the parent itself cannot reach. Example features of interest could include steep inclines and confined spaces, such as overhung rocks and caves on Mars, or "chaos terrains" on the surface of Europa.



NASA JPL researcher Aaron Curtis testing snow-tailored PUFFER at Mt. Erebus in Antarctica. (Credit: Brendan Hodge.)

**Status and Future Plans:** PUFFER has successfully completed initial field tests in both the Mojave Desert and Mt. Erebus in Antarctica. The Mojave Desert tests evaluated mobility on Mars-analog terrains, while the

Antarctica testing evaluated snow and ice mobility. The team is currently preparing next-generation prototypes for expanded field tests, which will integrate new instruments such as cameras and a microscope.

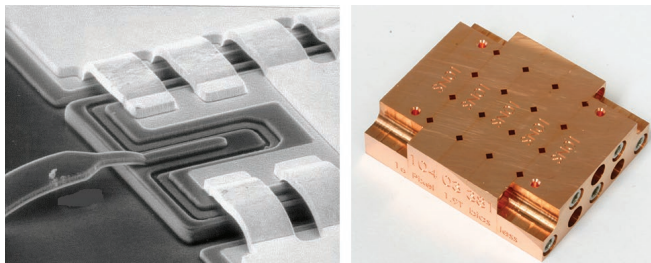
**Sponsoring Organization:** The PUFFER technology is jointly funded by SMD's Planetary Science and Earth Science Divisions, and by the Space Technology Mission Directorate (STMD) as part of the Game Changing Development (GCD) Program. In addition, the project's small business partner, Distant Focus Corporation, has received funding through the NASA Small Business Innovation Research (SBIR) office for development of a novel folded optic microscope for PUFFER. The PUFFER effort is being led out of NASA Jet Propulsion Lab, with collaborators at the University of California, Berkeley; Distant Focus Corporation (Champaign, IL); and Pioneer Circuits Inc. (Santa Ana, CA).

## FAR-INFRARED INSTRUMENT TO MAP STAR FORMATION IN THE UNIVERSE

**Technology Development:** Questions about how and when stars are formed continue to tug at human curiosity. Star formation is governed by gravity and heat. Gravity causes molecular clouds to collapse and eventually form stars and planetary systems, but to complete the process, heat needs to be continuously removed from the cloud. Hence, ionized carbon and neutral oxygen—the two major coolants of the interstellar medium (ISM)—are the best indicators of star-forming regions. New technology is being developed that will

allow spaceborne telescopes to make high-resolution multi-pixel maps of the universe, which will help scientists understand why star and planet formation is common in some regions of the universe, while other regions are dormant. The technology utilizes state-of-the-art Schottky diodes that enable a space telescope to observe and map deep-space regions. The Schottky diodes work at the frequencies required to detect ionized carbon and neutral oxygen—1.9 and 2.06 THz respectively. The smallest feature of these diodes is less than one micron (a human hair is typically 50 microns in diameter).

To date, only a single-pixel receiver has been flown in space. The multi-pixel technology NASA is developing allows tens and hundreds of these Schottky diodes to be packaged in metal enclosures, which will allow scientists to map large areas of the sky simultaneously. In 2016, NASA researchers demonstrated the first 16-pixel camera that worked at 1.9 THz. To implement multi-pixel THz cameras, the development team investigated a concept for packaging the diodes in very precisely machined thin metallic plates that are then stacked. To create a 16-pixel source, five metal plates—each about 5 mm thick—must be machined very precisely to obtain alignment tolerances better than 10 microns.



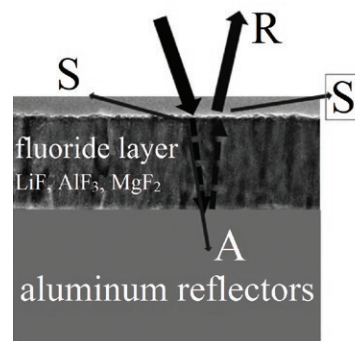
Close-up of a Schottky diode, showing the air-bridge that connects the anode (left). The 16-pixel module on the right is made with 5 metal plates that are precisely machined to achieve alignment tolerance better than 10 microns.

**Impact:** This multi-pixel far-infrared technology will enable NASA space telescopes to take “pictures” of the universe that will allow scientists to better understand the chemical and physical processes involved in the birth of new stars.

**Status and Future Plans:** Now that the first 16-pixel camera has been demonstrated, the NASA team is working to increase the sensitivity and pixel count so that the technology can be used on future NASA space missions.

**Sponsoring Organization:** The Astrophysics Division’s SAT program provides funding for this technology development effort to project lead Imran Mehdi at NASA Jet Propulsion Laboratory (JPL).

## COATED MIRRORS ACHIEVE RECORD-SETTING FAR ULTRAVIOLET REFLECTANCE LEVELS



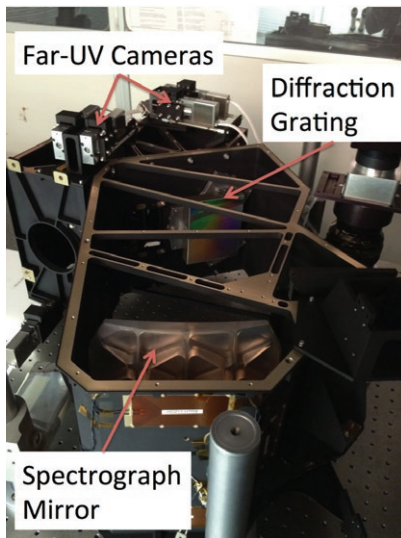
Schematic cross-section of aluminum film overcoated with a fluoride layer with low absorption (A) and low scattering (S) to provide maximum reflectance (R).

### Technology

**Development:** In 2016, scientists at Goddard Space Flight Center (GSFC) produced mirrors with the highest reflectance ever reported in the far-ultraviolet (FUV) spectral range (100-200 nm). To develop these mirrors, the team developed a new three-step physical vapor deposition

process to coat aluminum mirrors with protective magnesium fluoride ( $MgF_2$ ) or lithium fluoride ( $LiF$ ) films to protect the aluminum from naturally occurring oxidation and boost its reflectance performance in the FUV.

**Impact:** These high-reflectance coatings will enable new types of instruments (particularly in the FUV spectral region) that can provide scientists with knowledge that could impact society. For example, NASA is developing a new set of Heliophysics satellites—including the Ionospheric Connection Explorer (ICON) and the Global-scale Observations of the Limb and Disk (GOLD)—that will employ these coatings. ICON and GOLD will have the higher sensitivity required to collect data about the forces at play in the near-space environment of Earth’s upper atmosphere. These atmospheric regions are very sensitive to space weather events and space climate, and monitoring them will help scientists understand the interactions between Earth’s ionosphere and solar winds that can drive extreme weather systems. In addition, these observations will enable researchers to understand disturbances that can lead to severe interference with communications and Global Positioning System (GPS) signals.



The ICON FUV spectrograph.

**Status and Future Plans:**

In 2016, NASA fully validated these protective coatings to ensure that they provide over 90% reflectance in the 133.6-154.5 nm range for the ICON and GOLD projects. The team is also investigating additional new types of fluoride coatings that can be used to protect aluminum to

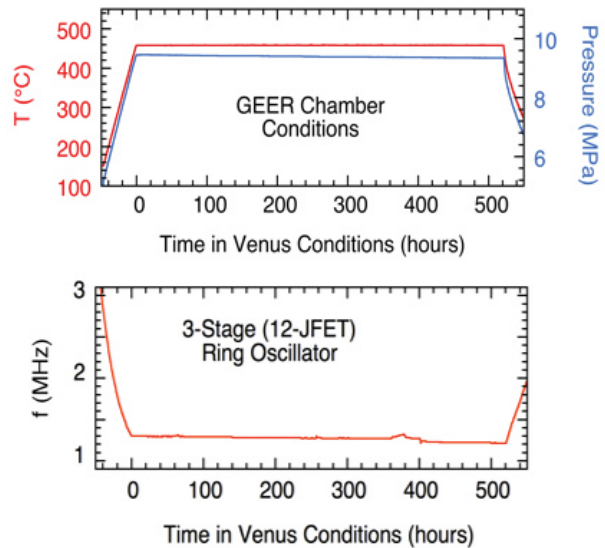
meet requirements of next-generation NASA observatories, such as the Large Ultraviolet/Optical/Infrared (LUVOIR) surveyor.

**Sponsoring Organization:** SMD previously supported development of these new coating technologies through an SAT grant and currently sponsors this work via the APRA program. The technology lead is Manuel Quijada at NASA GSFC.

**ELECTRONICS DEMONSTRATE OPERABILITY IN SIMULATED VENUS CONDITIONS**

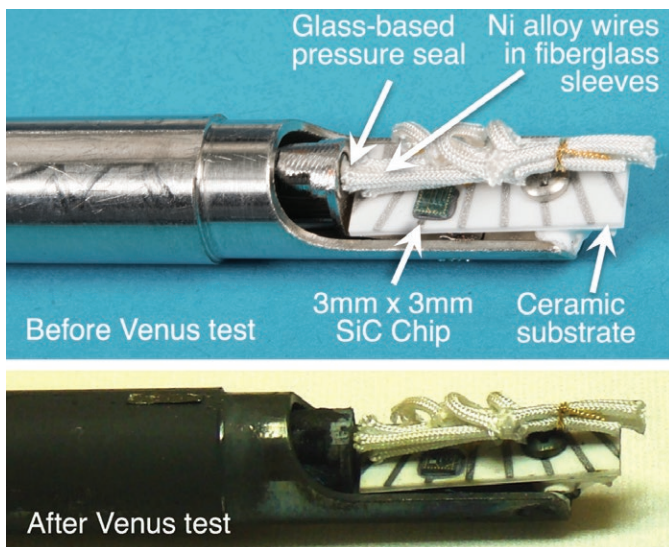
**Technology Development:** NASA's future planetary exploration efforts, including missions to Venus, require electronics capable of surviving temperatures of 470° C and above for long durations. Such durable electronics eliminate the need for cooling systems to enable sustained operations. Previous operation of electronics at Venus surface conditions (e.g., in Venus missions) has been limited to a few hours in a protected pressure/temperature enclosure, due to the extreme environment. Standard electronics used commercially and for planetary exploration are based on silicon semiconductors, which do not operate at Venus temperatures. A team at NASA Glenn Research Center (GRC) has been working to develop high-temperature electronics based on silicon carbide (SiC) semiconductors that can operate at Venus temperatures and above. Recently, the team demonstrated that a variety of the world's first moderately complex SiC-

based microcircuits (tens or more of transistors) could withstand up to 4000 hours of operation at 500° C. These demonstrations included core circuits such as digital logic circuits and analog operational amplifiers that are used throughout electronic systems.



Top: GEER replicates Venus simulated surface conditions, including temperature, pressure, and chemical composition. Bottom: High temperature ring oscillator continues stable operation in these "Venus conditions" for 521 hours.

Testing of two these circuits occurred in the Glenn Extreme Environments Rig (GEER), which simulates Venus surface conditions including high temperature and pressure. In April 2016, the team demonstrated a SiC high-temperature 12-transistor ring oscillator at Venus surface conditions (460° C, 93 atm pressure, supercritical CO<sub>2</sub> and trace gases) in the GEER for 21.7 days (521 hours) with good stability throughout the entire test. This Venus surface demonstration of moderately complex electronics is a significant world record—orders of magnitude in duration beyond any other Venus surface condition electronics demonstration. Testing in Venus conditions was ended after 21 days for scheduling reasons; similar ring oscillator circuits have shown thousands of hours of operations at 500° C in Earth-air ambient oven conditions.



SiC high-temperature electronics before and after testing in Venus surface conditions (rugged operation for extended durations). (Credits: top: Marvin Smith, NASA GRC; Bottom: David Spry, NASA GRC)

**Impact:** These advances are a paradigm shift that broadly enables new science exploration, especially for the Venus surface. SMD began a project in FY17—the Long-Life In-situ Solar System Explorer (LLISSE)—that will incorporate these new SiC electronics. LLISSE is developing a functioning prototype of a low-cost scientific probe capable of providing basic, but high-value, science measurements from the surface of Venus continuously for months or longer. Such a probe was not viable previously, and will revolutionize our understanding of the Venus surface. This new technology also impacts potential development of probes exploring the Gas Giants (Jupiter, Saturn, Uranus and Neptune) or the surface of Mercury. SiC-based electronics could also enable an intelligent aeronautics engine to monitor and respond to its own health state, and could be used in a range of commercial applications, such as deep oil well drilling or industrial processing.

**Status and Future Plans:** In August 2016, the team completed fabrication of “next-generation” extreme temperature integrated circuit wafers featuring significantly more complex digital and analog circuits (more than 100 transistors). In October, the team initiated prolonged 500° C testing (Earth-air atmosphere) of “next-generation” integrated circuits with more than 100 transistors. Plans include producing increasingly complex high temperature SiC electronics to meet the needs of the LLISSE project and other applications.

NASA will use a “design and build” approach to increase the capabilities of the basic electronics components, while providing new circuit types as needed for specific applications.

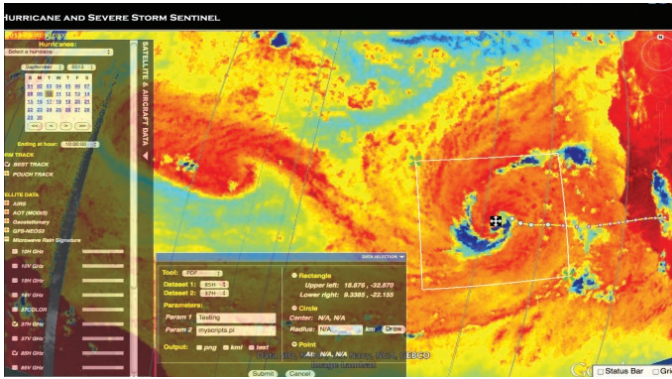
**Sponsoring Organization:** Multiple projects have supported this technology development in 2016. PSD’s PICASSO program sponsored work to develop a range of SiC core circuits for multiple applications and missions. SMD’s LLISSE Project worked to refine high-temperature SiC circuits for use on a Venus surface lander. Additionally, the NASA Aeronautics Research Mission Directorate’s Transformative Tool and Technologies Project supported development of high-temperature electronics for aeronautic engine applications.

## TROPICAL CYCLONE INFORMATION SYSTEM UPDATED TO INCLUDE NEW SATELLITE DATA SETS

**Technology Development:** The Tropical Cyclone Information System (TCIS) is a tool that fuses hurricane models and observations within a web-based system to improve forecasting capabilities. TCIS provides scientists with the capability to overlay user-selected observational data on top of a variety of user-selected model predictions, and to perform online analysis of models and observations. TCIS required development of processing techniques to enable multi-source data fusion across hurricane forecast models, satellite data, and in situ sensors. The TCIS team also developed tools to manage the validation and assessment of model comparisons to more easily evaluate the performance of different numerical models. These online, interactive visualization techniques are ideal for analyzing highly complex systems like hurricanes.

**Impact:** By bringing together near real-time data and a 12-year global data archive within a visualization portal, TCIS is enabling research about hurricane processes, helping to validate and improve models, and assisting in algorithm and data assimilation techniques.





This screen capture from the TCIS tool shows some of the enhancements to interactive region selection, model and data acquisition, statistical comparison, and visualization.

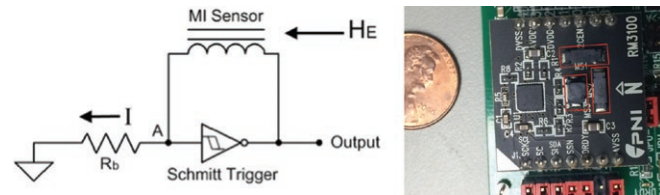
**Status and Future Plans:** In 2016, the TCIS team unveiled an updated portal that presents ocean vector winds from two scatterometer missions: NASA's Rapid Scatterometer on the International Space Station (ISS-RapidScat) and the European Advanced SCATterometer (ASCAT). The updated system has been adopted by the RapidScat project for their analysis work. The TCIS team is also using the system to review wind and precipitation fields to investigate whether the rapid intensification seen during 2016's Hurricane Matthew was predictable, based on satellite observations alone. In a previous study conducted in late 2015, products from TCIS were presented to personnel at the National Oceanic and Atmospheric Administration (NOAA) National Hurricane Center and the Hurricane Research Division (HRD) for use in analyzing Hurricane Joaquin. The output from a TCIS online analysis tool, developed in collaboration with HRD, suggested the potential for rapid intensification several hours before it happened.

**Sponsoring Organization:** The Earth Science Division sponsors development of TCIS via the AIST program. The PI is Svetla Hristova-Veleva at NASA JPL.

## “BOOMLESS” MAGNETOMETERS WILL ENABLE SMALL SATELLITE CONSTELLATIONS TO COLLECT MAGNETIC MEASUREMENTS

**Technology Development:** Researchers from the University of Michigan (UM) and NASA GSFC are partnering to develop new types of magnetometers for use on future small satellites. These new instruments not only fulfill stringent requirements for low-amplitude and high-precision measurements, they are also enabling

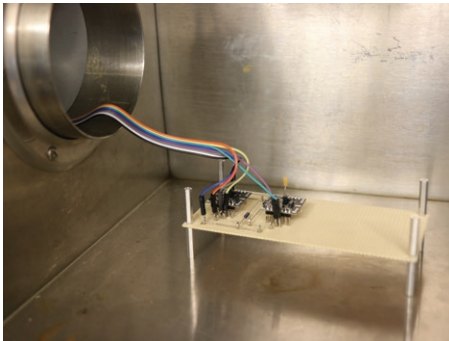
the team to develop a new approach to achieving high-quality magnetic measurements from space, without the need for a boom. Typically, space-based magnetometers are deployed on a boom that extends from the space vehicle to reduce exposure to magnetic noise emanating from the spacecraft that could potentially contaminate measurements. The UM/NASA team has developed algorithms to identify and eliminate spacecraft magnetic noise, which will allow placement of these economical, science-grade instrument magnetometers on and inside the satellite bus, instead of on a boom.



Left: The functional diagram of the induction magnetometer circuit. HE is the external magnetic field to be measured. Right: PNI Induction magnetometer compared to a penny. The square chip is the magnetometer electronics and the three rectangular blocks (highlighted in red) are the three axis sensors. (Credit: Mark Moldwin, UM)

One of the new types of instruments—called an induction magnetometer—also shows considerable promise over other chip-based technologies and provides characteristics consistent with modern magnetometers. The new magnetometer is a modified commercial magneto-inductive magnetometer from PNI Sensor Corporation. In the new induction magnetometer, the magnetic field is measured by counting the time between flips of the magnetic induction of the circuit, which is dependent on the strength of the applied DC field. As illustrated by the functional diagram shown above (left), the magnetometer includes a Schmitt Trigger for counting pulses. In the figure, HE is the external magnetic field parallel to the coil. The total field that the sensor experiences is due to the external field and the field generated by the circuit. The time between oscillations or trigger flips is dependent on the strength of the external field, and therefore, the DC field can be measured by simply counting the number of flips or triggers. Since the device is a simple counter, it allows the elimination of radiation-sensitive analog-to-digital converters and enables temperature sensitivities of the new sensor to be accounted for directly in the circuitry.

**Impact:** One of NASA's goals is to support the development of small, low-mass, low-power-consumption, and low-cost space instruments. This new technology will result in a small, lower mass, less expensive magnetometer instrument concept. The new sensors and approach will enable future constellations of small satellites to measure the background magnetic field environment in space, which will help scientists to understand space weather and the structure of the space environment.



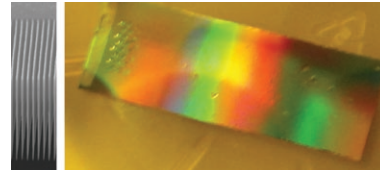
A dual-sensor undergoing initial thermal vacuum testing. (Credit: Bret Bronner, UM)

**Status and Future Plans:** In 2016, the team accomplished a number of objectives: (1) characterizing the commercial sensor (sensitivity, linearity and frequency

response), (2) understanding its performance based on changes to various internal electronic settings (cycle count and sampling rate), (3) development of a multi-sensor system (to over-sample with multiple sensors, as shown in the test chamber above) that included incorporating a micro-processor to control and take data without using a lab computer, (4) commencement of thermal cycle testing, and (5) completion of initial vibration testing. The team is currently working with a UM CubeSat project—the Miniature Tether Electrodynamics Experiment (MiTEE)—that will fly two internal magnetometers and one at the end of a short boom. Though MiTEE will be using a different commercial magnetometer, the UM/NASA team will be able to test its noise cancellation algorithm.

**Sponsoring Organization:** The STMD Smallsat Technology Program and the Heliophysics Division's H-TiDeS program are supporting this effort. Dr. Eftyhia Zesta at NASA GSFC and Professors Mark Moldwin and Jamie Cutler at the University of Michigan lead this project.

## HIGH-RESOLUTION X-RAY GRATINGS ENABLE STATE-OF-THE-ART SPECTROMETER



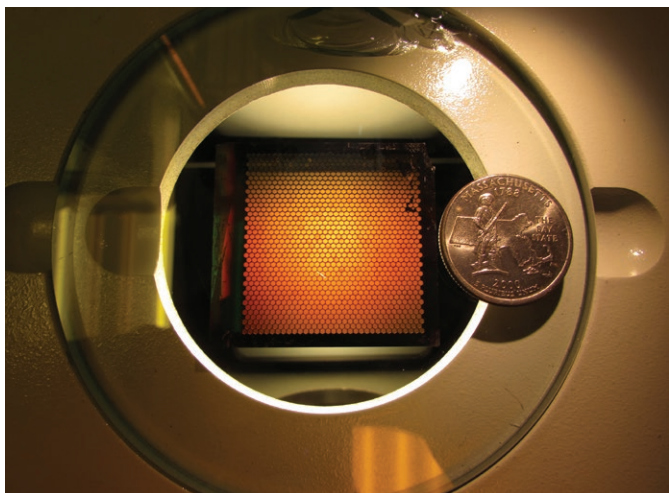
Electron micrograph of cross-section through a CAT grating showing the atomically smooth nano mirrors (left), and a tested 32 mm-wide CAT grating coated with platinum using atomic layer deposition (right). (Credit: R. Heilmann, MIT, and A. Bruccoleri, Izentis, LLC)

### Technology Development:

X-ray-optics technology has progressed such that future astrophysics X-ray observatories will have orders-of-magnitude better performance than

existing observatories such as NASA's Chandra X-ray Observatory. High-resolution soft X-ray spectroscopy offers particularly useful observations that can provide information about the evolution of large-scale structure in the universe, conditions near black holes, stellar atmospheres, and more. Spectrometers employing novel critical-angle transmission (CAT) X-ray gratings promise spectral resolving power,  $R$ , as high as 5000—at least 5-10 times that of present instruments. In 2016, an SMD-sponsored team produced and successfully demonstrated this new technology. A high-resolving-power, soft X-ray objective grating spectrometer for deployment in space requires a lightweight focusing optic with very good angular resolution and gratings that can disperse X-rays to the largest possible angles with high efficiency and minimal aberrations. Realizing the challenging CAT grating design required almost a decade of development and breakthroughs in advanced nanofabrication technology including patterning, etch and atomic level deposition. Demonstrating this capability in the lab was challenging, however, and required a combination of unique state-of-the-art nanofabrication processes and test hardware such as a long X-ray beamline and a spectrally narrow source.

**Impact:** Future X-ray missions employing this technology will provide vastly improved absorption- and emission-line spectroscopy of high-energy astrophysical sources such as black hole winds and hot gas in the cosmic web. Additional potential applications for CAT gratings include spectrographs for observations of the heliosphere, optics for high-power X-ray facilities, and filters for neutral-particle measurements in Earth's magnetosphere.



Recent large-area CAT grating next to a U.S. quarter coin. (Credit: R. Heilmann, MIT, and A. Bruccoleri, Izentis, LLC)

**Status and Future Plans:** In 2016, three institutions collaborated to produce and demonstrate this new technology. The Space Nanotechnology Lab at the Massachusetts Institute of Technology (MIT) Kavli Institute provided state-of-the-art 200-nm-period ultra-high-aspect-ratio silicon CAT gratings coated with a thin layer of platinum that enabled diffraction to angles up to 18 times larger than those supported by Chandra spectrometers. The 100-m-long Marshall Space Flight Center Stray Light Facility served as the beam line, and the X-ray optics group at Goddard Space Flight Center provided a lightweight high-resolution focusing optic. Preliminary analysis from this demonstration showed  $R$  much higher than 10,000—believed to be a world record for grating spectroscopy in the X-ray band. CAT grating technology continues to be refined to achieve higher efficiency and larger gratings. This technology is currently being proposed for use on an Explorer satellite mission named Arcus and studied for potential use in the Lynx mission concept, a potential successor to Chandra in the next decade.

**Sponsoring Organization:** The Astrophysics Division supports development of this new technology by providing funding via the SAT program. Development leads include Mark Schattenburg and Ralf Heilmann of the Massachusetts Institute of Technology and Alexander Bruccoleri of Izentis, LLC.

## MEASUREMENT VALIDATION FLIGHTS FOR DOPPLERSCATT INSTRUMENT SHOW PROMISE

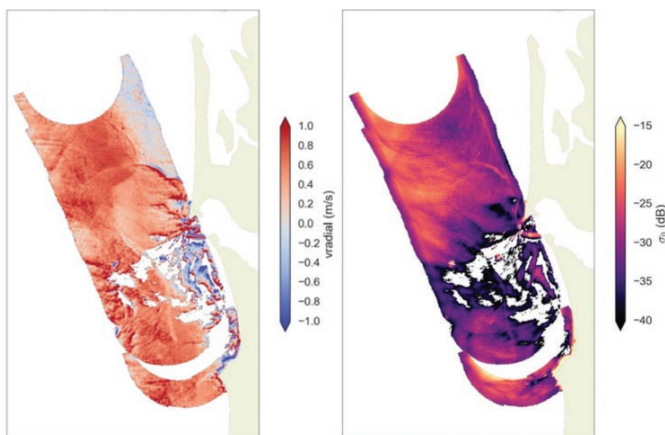
**Technology Development:** Researchers at NASA JPL have successfully built and demonstrated the first instrument capable of taking simultaneous measurements of ocean surface winds and water currents. DopplerScatt, a spinning Ka-band Doppler scatterometer, conducted several validation flights onboard a Department of Energy B200 aircraft in September 2016 over coastal Oregon and Washington. Scientists study ocean surface currents because they impact heat transport, surface momentum and gas fluxes, ocean productivity, and marine biological communities. Ocean currents also have societal impacts because they affect shipping and disaster management (e.g., oil spills). There is an intrinsic two-way coupling between ocean currents and surface winds; concurrent measurements of the two enable the understanding of the relevant air-sea interaction. The primary goal of the September flights was to demonstrate DopplerScatt's ability to take simultaneous measurements of ocean surface winds and water currents. The flights were also an opportunity to investigate the interaction between the Columbia River plume and ocean waters, fresh-water mixing and transport, and coastal ocean circulation.



The B200 aircraft and pilots. The DopplerScatt radome is the white, cone-shaped object protruding from the belly of the airplane. (Credit: Perkovic-Martin/JPL)

**Impact:** DopplerScatt's unique ability to simultaneously measure winds and currents improves the accuracy of both individual measurements. The airborne DopplerScatt

lays the groundwork for an eventual spaceborne scatterometer with similar capabilities.

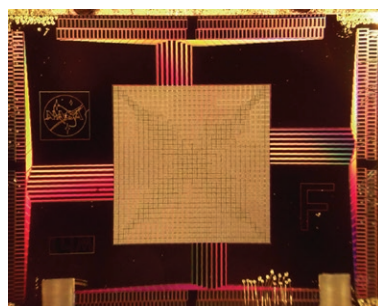


Left: Radial current velocity near the Columbia River estuary from a September 13, 2016 flight, corrected for aircraft motion. Right: Radar backscatter cross-section, also from September 13, 2016. (Credit: Perkovic-Martin/JPL)

**Status and Future Plans:** Although data from the flights is still being processed, the demonstrations appear to have been successful. Water current velocity was mapped around the Columbia estuary and the radar backscatter will be exploited to retrieve surface winds. Response from the science community has been positive and the instrument may be used to support a 2017 effort to study the effects of the Mississippi River on ocean mixing, circulation, and sediment and nutrient transport.

**Sponsoring Organization:** NASA's Earth Science Division provides funding for DopplerScatt via the IIP to PI Dragana Perkovic-Martin at NASA JPL.

## AN X-RAY CAMERA THAT CAN RESOLVE TENS OF THOUSANDS OF X-RAY COLORS



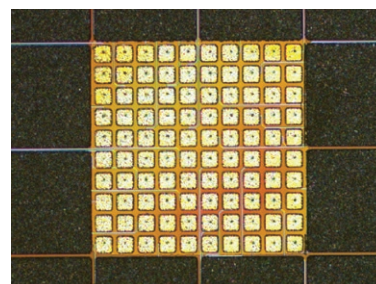
A 32x32 TES X-ray microcalorimeter array that is a candidate for use in the Athena X-IFU demonstration model. The individual, closely packed Au/Bi absorbers are arrayed on a 0.25 mm grid.

A non-dispersive spectrometer that uses an equilibrium approach to energy measurement—the energy of an X-ray photon heats an isolated thermal mass, and the

### Technology

**Development:** NASA is part of an international team developing a cutting-edge microcalorimeter X-ray camera that will provide extraordinarily detailed information about energetic cosmic phenomena. An X-ray microcalorimeter is a

temperature change is measured. The ultimate energy resolution is determined by how well the temperature pulse can be measured against a background of thermal fluctuations; thus, high-resolution spectrometers must be operated at very low temperatures ( $< 0.1$  K). The basic idea for these instruments was proposed three decades ago, but since then, a variety of implementations and optimizations have been developed, with a steady improvement in capability and an increase in the number of imaging elements (pixels).

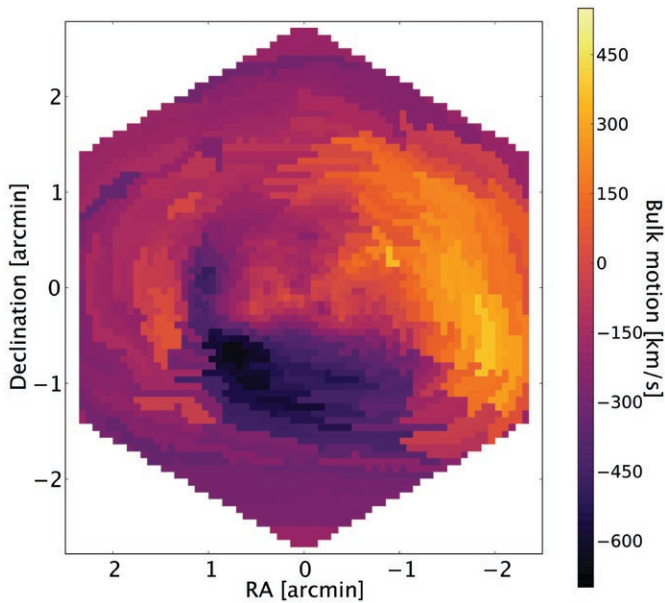


An example of a hybrid array consisting of a 10 x 10 array of small-pixel TESs with Au absorbers (0.05 mm pitch) surrounded by an array of larger pixels with composite Au/Bi absorbers (0.25 mm pitch). Such an array was considered for X-IFU to provide a central region optimized for higher spectral resolution or higher count rates.

With each improvement, new mission concepts are developed that require even larger arrays. The NASA/Japan Aerospace Exploration Agency (JAXA) Soft X-ray Spectrometer (SXS) instrument onboard the JAXA Hitomi mission had 36 pixels, but the X-ray Integral Field Unit

(X-IFU) instrument that will fly on the European Space Agency's Athena mission requires an array of about 4000 pixels, each about 0.25 mm wide (covering 5 arc seconds of the sky). X-IFU will be a groundbreaking X-ray camera capable of distinguishing tens of thousands of X-ray colors. As part of the X-IFU consortium, NASA is developing the superconducting transition edge sensor (TES) array employed on the instrument. These sensors, composed of Molybdenum/Gold TES thermometers and Gold/Bismuth X-ray absorbers, achieve better than 2.5 eV resolution.

**Impact:** Cosmic phenomena that produce X rays characterize the evolution of cosmic structures on both large and small scales. High-resolution X-ray spectroscopy can determine density and temperature, identify ions and determine their velocities, and enable scientists to study effects such as turbulence or the environment near supermassive black holes. Combining imaging with spectroscopy, a microcalorimeter instrument probes dynamics and variations within spatially extended objects such as supernova remnants and galaxy clusters with unprecedented sensitivity.



Simulated map of line-of-sight velocities in the X-ray emitting gas in a galaxy cluster like the Perseus cluster, as determined from the high-resolution X-ray spectrum that the X-IFU will measure for each pixel. (Credit: left panel of Fig 2 in Barret et al. 2016, Proc. SPIE. 9905, Space Telescopes and Instrumentation 2016: Ultraviolet to Gamma Ray, 99052F).

**Status and Future Plans:** In 2016, the NASA team focused on working with partners at SRON, the Netherlands Institute for Space Research, to prepare for an X-IFU demonstration model incorporating a kilopixel TES array. Because the planned readout for X-IFU uses frequency-division multiplexing, which involves applying alternating voltages to the TES thermometers, the near-term focus has been on determining the optimal pixel design for that mode of operation. Important progress was also achieved using backup multiplexing technologies that apply a constant voltage to the TES thermometers (time-division and code-division). A time-division multiplexing demonstration of a column of 32 TES pixels achieved 2.55 eV average energy resolution at 6 keV at a speed appropriate for the original X-IFU baseline. The team completed the layout for a full-sized X-IFU prototype array, and in the next year these prototypes will be fabricated and tested. The team also successfully demonstrated that pixels with different characteristics (width, X-ray absorber materials and thickness, and superconducting transition temperature) can be incorporated into a single array, should it be determined to be optimal to do so on X-IFU or another mission.

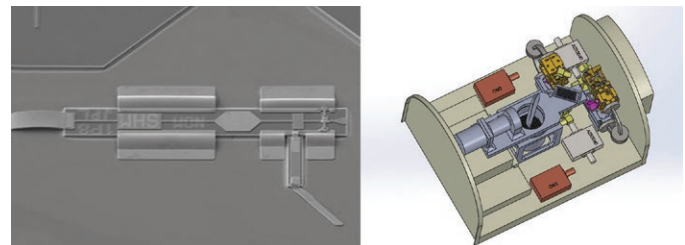
**Sponsoring Organization:** The NASA Astrophysics Division has been investing in X-ray microcalorimeter

technology for three decades. The TPCOS program has funded recent progress via an award to a team including members at GSFC; the National Institute of Standards and Technology in Boulder, Colorado; and Stanford University. PI Caroline Kilbourne and Simon Bandler of NASA GSFC lead this technology development effort.

## NEW ATMOSPHERIC WIND/TEMPERATURE SENSOR TO IMPROVE SPACE WEATHER PREDICTION

**Technology Development:** Global wind and temperature measurements in the lower thermosphere (100-150 km above Earth) are the two most important variables needed to accurately predict space weather and climate change. An innovative technique is being developed jointly by the Johns Hopkins University Applied Physics Laboratory, GSFC, and JPL to make these measurements using the atomic oxygen emission at 2.06 THz (145  $\mu\text{m}$ ).

A new sensor, called the TeraHertz Limb Sounder (TLS), will make these critical measurements under a wide range of observation conditions (e.g., day and night, with and without aurora present) from a low Earth orbit. Not only will TLS measurements enable scientists to study neutral atmosphere interactions with the ionosphere and magnetosphere above, they will improve our fundamental understanding of the mechanisms and effects in Earth's upper atmosphere and other planetary and stellar atmospheres. The data will also help researchers understand how the upper atmosphere is affected by solar variability (i.e., radiation, magnetized solar winds, and energetic particles) and lower-atmospheric disturbances—critical geophysical processes that influence numerous space weather phenomena that present hazards to spacecraft, humans in space, and technological infrastructure on the ground.



Close-up of the 2.06 THz Schottky diode mixer (left); a computer-generated model of the full TLS instrument (right). (Credit: NASA JPL)

The TLS instrument is enabled by a high-sensitivity gallium arsenide (GaAs)-diode-based heterodyne receiver that operates at room temperature. In 2016, the team developed the high-frequency Schottky diode shown on the previous page, which mixes the incoming signal from 2.06 THz down to an intermediate frequency band to measure spectral emission features from atomic oxygen in the atmosphere. This advanced mixer technology can be used to build compact, low-mass and low-power instruments for NASA's small satellite missions.

**Impact:** TLS development will mature and optimize a low-noise, high-sensitivity THz receiver to advance Heliophysics science in future space weather missions with reduced cost and schedule risks. This development effort focuses on the receiver system integration, optimization, and demonstration of key subsystem performance. This THz receiver system is designed to operate at an ambient temperature in space using passive radiators, thus removing the need for a dedicated resource-demanding cryocooler.

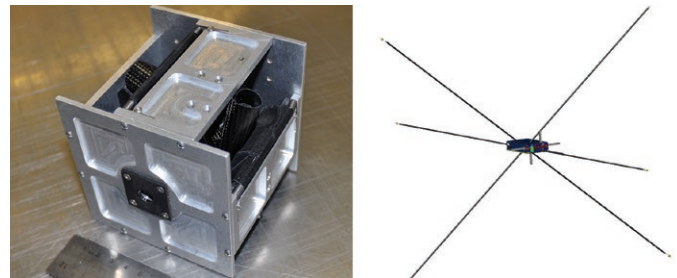
**Status and Future Plans:** In 2016, the team completed development of the TLS receiver concept and successfully designed and fabricated the Schottky diode mixer. Ongoing research is focused on building a model prototype instrument and making receiver-sensitivity measurements to verify receiver performance.

**Sponsoring Organization:** The SMD Heliophysics Division's H-TIDeS program provides the funding for this technology development effort. The PI is Dr. Jeng-Hwa (Sam) Yee at the Johns Hopkins University Applied Physics Laboratory.

## TRI-AXIAL DOUBLE PROBE WILL ENABLE SMALL SPACECRAFT TO MEASURE ELECTRIC FIELDS

**Technology Development:** A team at NASA GSFC is working to develop new technology that will enable small satellites to measure direct current (DC) and alternating current (AC) electric field vectors in space. One element of this new technology involves development of coilable, narrow, composite booms, which when deployed, have the necessary stiffness and straightness to enable electric field double probe measurements to be gathered in space. Double probe measurements gather the potential difference

along a given axis or component of the electric field; tri-axial measurements gather all three perpendicular components of the vector. These newly developed booms include small wires extending the length of the tubes to isolate the sensor elements at the ends from the main boom element. In addition, the team has successfully miniaturized the main electronics of the probes themselves without any loss of capability or sensitivity.



Left: Electric field booms compactly stowed in the CubeSat volume (10 cm on a side). Right: Six booms extend sensors from the main CubeSat body to distances of 5m, tip-to-tip, enabling triaxial or vector electric field measurements. (Credits: CTD and NASA GSFC)

**Impact:** Electric field instruments gather data to address fundamental, physical processes including the flow of energy in a wide range of space environments. The development of such small tri-axial electric field double probes will enable inexpensive sampling of Earth's ionosphere, allowing researchers to learn more about a host of important scientific phenomena in geospace—including lightning, aurora, radio waves, and large-scale instabilities.

**Status and Future Plans:** In 2016, the NASA team developed a tri-axial boom system in conjunction with Composite Technology Development (CTD), Inc. of Lafayette, Colorado. CTD has produced coiled composite booms that will compactly fit inside the 10 cm<sup>3</sup> volume of a CubeSat, yet, when deployed, will provide a tri-axial 5m tip-to-tip boom system. The team also developed the associated electric field electronics that will fit inside the CubeSat. During the coming year, researchers will complete testing and mechanical accommodations with other instruments and CubeSat subsystems, preparing a complete prototype experiment for spaceflight.

**Sponsoring Organization:** This research is sponsored by the Heliophysics Division via the H-TIDeS program. The PI and lead Co-investigators are Drs. R. Pfaff and D. Rowland at NASA GSFC.

## ADVANCED THERMOELECTRIC TECHNOLOGY: POWERING SPACECRAFT AND INSTRUMENTS TO EXPLORE THE SOLAR SYSTEM

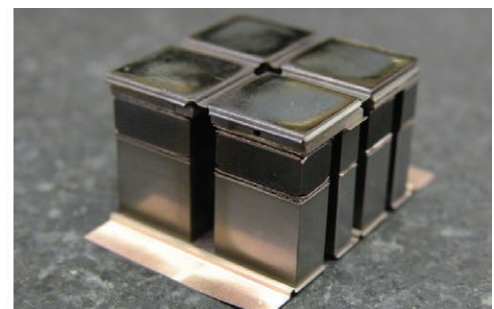
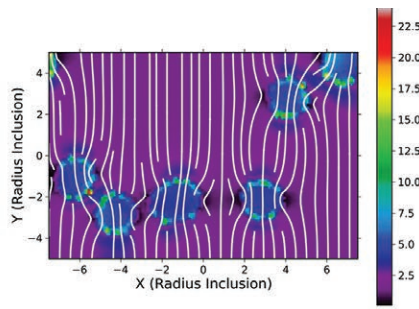
**Technology Development:** Radioisotope power systems (RPS) provide the efficient, long-lasting power sources vital to the success of numerous NASA space missions. RPS convert heat generated from the radioactive decay of plutonium-238 oxide into electricity that powers spacecraft and instruments. The current “off-the-shelf” flight-proven RPS is the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG), which relies on power-generating thermoelectric (TE) couples using heritage materials (lead-telluride/tellurium-antimony-germanium-silver alloys). NASA SMD is sponsoring technology development efforts to improve Radioisotope Thermoelectric Generator (RTG) performance, both in terms of the thermal-to-electric conversion efficiency (~ 6.3% at beginning of life - BOL) and the degradation rate during the 17-year design life.

NASA SMD’s steady investment in thermoelectric materials and device research and development has led to significant technology breakthroughs. Recently, researchers have discovered several classes of new high-efficiency materials with an excellent potential for infusion into future RTGs. These materials—skutterudites (SKD, based on  $\text{CoSb}_3$ ), Zintl phases (such as  $\text{Yb}_{14}\text{MnSb}_{11}$ ) and lanthanum telluride ( $\text{La}_{3-x}\text{Te}_4$ )—possess highly complex crystal structures, have excellent thermal and chemical stability across the range of very low temperatures (1273 K to 473 K) characteristic of the space environment where RTG operate, and offer significant opportunities for further increases in performance. In 2016, initial testing of new thermocouple devices combining these materials

demonstrated a factor of two improvement in conversion efficiency over heritage technologies.

**Impact:** Industry is currently maturing lower-temperature (up to 900 K) SKD materials technology for potential infusion into an Enhanced Multi-Mission Radioisotope Thermoelectric Generator (eMMRTG). The eMMRTG would offer a 25% boost in power at BOL that would grow to least 50% at end-of-design life (17 years after BOL), thanks to its estimated lower degradation rate. Combining this skutterudite technology with the higher-temperature 14-1-11 Zintl and  $\text{La}_{3-x}\text{Te}_4$  materials into segmented device technology (segmented elements combine several materials into a single, wide-temperature, high-efficiency device that utilizes each material in its most efficient temperature range) could enable more capable RTG concepts. Such concepts could be modular, accommodate a wide range of power system sizing (from tens to hundreds of watts), and achieve much higher specific power than the MMRTG. This SMD-funded technology has also attracted interest for application to various terrestrial fields of use concerning industrial waste heat recovery and energy efficiency.

**Status and Future Plans:** Several significant technology developments were completed in 2016. A new method—composite assisted funneling of electrons (CAFE)—was identified for improving the efficiency of TE materials such as 14-1-11 Zintls and  $\text{La}_{3-x}\text{Te}_4$ . The CAFE mechanism does not appear to be material-specific and could provide a new method to improve the efficiency of a wide range of thermoelectric materials. For SKD technology, SMD-sponsored efforts focused on developing device component technologies resilient enough to operate within the hermetically sealed converter “cavity” of the eMMRTG. Researchers also changed the materials used to metallize the SKD elements and altered the composition of the



Left: New industry-produced SKD couples that are resilient enough to operate in the eMMRTG hermetically sealed converter cavity. (Credit: S. Keyser, Teledyne Energy Systems, Inc.) Center: Monte Carlo simulation of heat flow across composite TE material with metal inclusions. (Credit: P. von Allmen, JPL/Caltech) Right: High-temperature segmented thermoelectric module technology with 2X efficiency gain over heritage RPS technology. (Credit: S. Firdosy, JPL/Caltech)

metallic bonding layers used to fabricate the couples. Extended performance testing in a relevant operating environment confirmed the resilience of the new SKD couple configurations to residual moisture and gases. Completion of the SKD technology maturation for a potential transition to the eMMRTG flight system development is currently scheduled at end of 2018.

**Sponsoring Organization:** PSD's Radioisotope Power System Program is providing funding to the Thermoelectric Technology Development Project (TTDP) managed by Jean-Pierre Fleurial at the NASA Jet Propulsion Laboratory (JPL). The TTDP is led by JPL and includes participation by the NASA Glenn Research Center, academia, and industry.

## GROUNDBREAKING X-RAY OPTICS WILL ENABLE FUTURE OBSERVATORIES



A Wolter-I mirror segment with a thickness of 0.6 mm. This mirror has a dimension of approximately 100 mm by 100 mm. Tens of thousands of mirror segments like this one will be aligned and integrated to make an assembly to achieve several  $m^2$  of effective area. (Credit: Bill Hrybyk)

**Technology Development:** An X-ray telescope is characterized by four parameters: angular resolution, effective area, mass, and production cost. Researchers at NASA GSFC have developed a new X-ray mirror technology that is expected to improve one or more of these parameters by at least an order of magnitude, compared to the mirrors currently employed on missions such as the Chandra X-ray Observatory and

the Nuclear Spectroscopic Telescope Array (NuSTAR). This mirror technology combines a polishing process used for fabricating optics of the highest quality with use of monocrystalline silicon—a material used in the semiconductor industry. Monocrystalline silicon is free of internal stress and thereby enables development of extremely thin (less than 1 mm) and lightweight (areal density less than  $2.5 \text{ kg/m}^2$ ) mirrors. The GSFC team has been working to perfect this technology since 2011, and in 2016 they developed a process to make Wolter-I (parabolic or hyperbolic) mirrors as thin as 0.5 mm with figure quality better than 3 arcsec—a tenfold improvement over the NuSTAR mirrors. In parallel, the team developed a bonding process that preserves the figure and alignment of these thin mirrors, while enabling them to sustain a typical space launch vibration environment.

**Impact:** This mirror technology will enable observation and study of supermassive black holes, galaxy clusters, and the centers of nearby galaxies, where myriad stellar binaries containing compact objects such as neutron stars and black holes reside. This monocrystalline silicon mirror technology has the potential to enable a quantum jump in capability with a mass and production cost comparable to today's technology. The modular nature of this mirror technology, where a large mirror assembly is constructed of many small mirror segments, makes it highly amenable to parallel and mass production, both of which are essential for meeting schedule and cost requirements of future missions. Likewise, this technology is also suitable for making mirror assemblies for missions of all sizes.

**Status and Future Plans:** The team will refine the mirror fabrication and bonding processes to improve the figure quality by at least an order of magnitude in the next five to ten years, so the technology will be ready to implement on a major X-ray observatory in the 2020s.

**Sponsoring Organization:** SMD's Astrophysics Division supports this development effort via the APRA and SAT programs, and William Zhang at GSFC is the PI.



## HIGH-EFFICIENCY STIRLING CONVERTOR DEMONSTRATES LONG-TERM PERFORMANCE



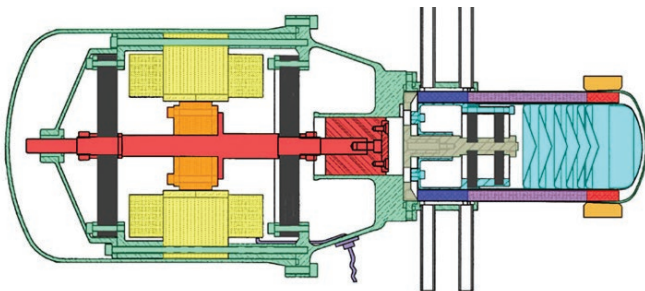
TDCs #13 and #14 on extended operation in the Stirling Research Lab. (Credit: NASA Glenn Research Center)

### Technology

#### Development:

NASA Glenn Research Center has been supporting the development of high-efficiency Stirling power convertors for potential use in Radioisotope Power Systems (RPS) for over

a decade. Stirling convertors are engines that convert heat into electricity by oscillating a linear alternator. Stirling power convertors in RPS can potentially reduce the amount of plutonium fuel required to achieve a given power level by a factor of four, all while maintaining the long life and high reliability needed to support space missions. In 2016, GRC researchers analyzed a long-term demonstration of Stirling power convertor technology, and the results indicate the promise of this technology for use in future missions.



TDC Cross Section (Credit: NASA Glenn Research Center)

In the early 2000s, several Stirling convertor prototypes were fabricated and placed on extended operation at GRC to demonstrate long life. Two of these units, designated Technology Demonstration Convertors (TDC) #13 and #14, have each accumulated 103,000 hours of operation (11.7 years). In 2016, the NASA GRC team completed an evaluation of the TDCs' performance and found no performance degradation, indicating that these units have demonstrated the reliability necessary for a long-life dynamic power convertor.

Despite the presence of moving components, these Stirling-cycle machines have achieved long life through

the elimination of wear mechanisms and use of advanced high-cycle components and high-temperature materials. Flexure bearings are used in the TDCs to suspend the moving components without any contact, while maintaining a close-clearance seal between the piston and cylinder. Developers designed the flexures that experience high-cycle oscillating stress to have a fatigue life well above the required life of the device. The high-temperature materials are designed for the required life as well.

**Impact:** Many missions that use RPS travel to the outer reaches of the solar system, and thus have long mission durations—in some cases as high as 17 years. Any power convertor integrated into an RPS must operate continuously during the entire mission. This long-term demonstration of dynamic power convertor reliability is a critical step in the realization of an improved RPS. Currently available RPS options use the radioisotope fuel's energy at an efficiency of approximately 6%. A Stirling-based RPS could boost this efficiency to 20% or higher, significantly increasing the power NASA science and exploration missions can obtain from the finite U.S. supply of plutonium-238. A Stirling-based RPS also has the potential to significantly increase the specific power of a generator, which could enable a new class of science missions by coupling RPS with electric propulsion.

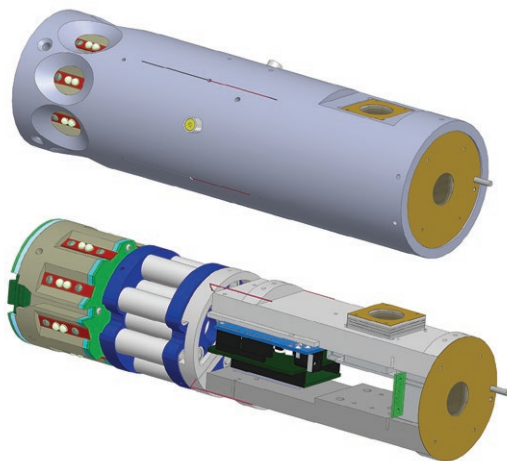
**Status and Future Plans:** The continuous power production of the two TDCs for over 11 years provides evidence that dynamic power conversion can be relied upon for space exploration. To confirm that minimal or no wear has been experienced by these convertors, one of the 103,000-hr TDC units will be disassembled for inspection. The other unit will continue operation to support reliability assessment of flexure-based free-piston Stirling convertors. PSD is currently examining several different dynamic convertors in an effort to develop a robust and reliable radioisotope generator to support future missions. Data from this long-term TDC demonstration will provide valuable insight regarding the potential use of Stirling convertors in future flight hardware.

**Sponsoring Organization:** PSD's Radioisotope Power Systems Program sponsors this technology development effort.

## SWARMS OF LOW-RESOURCE SENSORS TO PROBE THE IONOSPHERE

**Technology Development:** NASA is sponsoring a team developing a new type of payload to collect ionospheric plasma data at multiple points near a suborbital main payload. These low-resource, easily reproducible payloads—called Bobs—were developed for the NASA Isinglass auroral sounding rocket mission (conducted in February 2017 at the Poker Flat Research Range in Alaska). Much of the current understanding of the ionospheric environment has been gathered from single-point measurements. However, there are fundamental questions about energy and disturbances in plasmas that require measurements at many points in time to understand.

The following parallel situation illustrates why such measurements are important. If a journalist reporting about hurricane conditions moves away from the coast over several days and reports improvement in the situation, it is not apparent whether conditions are improving with time or with distance from the coast. On the other hand, several reporters deployed simultaneously in multiple positions could distinguish the effects of time from those of space. Likewise, a swarm of instruments can differentiate changes in space and time that a single-point instrument cannot.



A SolidWorks image of the Bob payload with (at left) and without its external housing (at right). (Image credit: T. Max Roberts)

Scientists have used NASA's sounding rocket program to collect multi-point ionospheric measurements before, but historically the sub-payloads have been complex, and therefore relatively expensive. The goal of this effort

was to develop sub-payloads that can carry plasma physics instrumentation, but are reproducible in large numbers. To develop the Bob sub-payloads, the team took advantage of the design of previous sub-payloads that were used to release chemicals, but did not contain instrumentation. The team reused the deployment and envelope parts of the design, but adapted the chemical release portion of the design into a small Arduino-based instrumentation package capable of local (several km) communications back to the main payload. The Bob sub-payloads each carry two thermal ion sensors (retarding potential analyzers) as well as a small commercial inertial measurement unit (IMU) like that found in a handheld video game controller.



The complete set of instrumentation just before delivery (Image credit: Dartmouth College)

**Impact:** The technology developed for the Bob sub-payloads will enable NASA to deploy low-resource

sensors to measure changes in the ionosphere at multiple locations at the same time. These economical sensor swarms will provide a detailed picture of ionospheric processes, enabling scientists to learn more about the complex systems at work in Earth's upper atmosphere.

**Status and Future Plans:** In 2016, the team studied the results of the 2015 test flight mission that successfully deployed two of the Bob sub-payloads over Wallops Island. Using information from this test flight, they finalized and improved the design of the Bobs to be used as Isinglass sub-payloads. In late summer of 2016, the team delivered ten copies of the Bob payload and associated instrumentation to NASA Wallops Flight Facility for integration with the other Isinglass instrumentation. At the time of this writing the Isinglass team was in the field for the launch campaign; four of the Bob sub-payloads were cleanly and successfully released from the Isinglass B main payload, and the science team is in the process of assessing the results.

**Sponsoring Organization:** SMD's Heliophysics Division provides funding to PI K. A. Lynch at Dartmouth College to support this technology development effort.

# TECHNOLOGY INFUSION

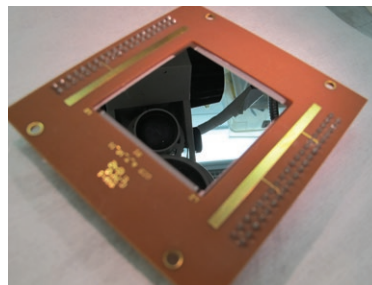
## HIGH-EFFICIENCY CHARGE-COUPLED DEVICES ENABLE ON-SKY OBSERVATIONS

**Technology Infused:** In 2016, NASA delivered three types of detectors developed for Ultraviolet (UV), Near UV (NUV), and Near Infrared (NIR) applications to several different projects involving on-sky observations. Development of these charge-coupled devices (CCDs) required several new processes formulated by NASA. Successful observations using the new CCDs validated detector performance, and next the Agency plans to refine these detectors for use in suborbital flight. The high efficiency and stable response of these CCDs make them ideal for astronomy applications, and each is tailored for a different type of observation.



2-D-doped EMCCD with custom AR coating for FIREBALL and Palomar observations. (Credit: Todd Jones)

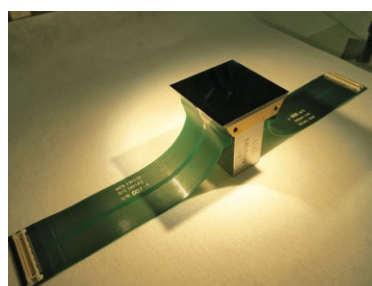
**Delta doped and custom coated Electron-multiplying Charge-coupled Devices (EMCCDs)**, with their high signal-to-noise ratio, are particularly suitable for faint signal detection of phenomena such as intergalactic medium, circumgalactic halos, and star formation outflows. In collaboration with e2v, Inc., the NASA team developed an EMCCD that is back-illuminated and that has an electronic band structure that is modified using two-dimensional (2-D) doping (i.e., delta doping and super-lattice doping). This process produces 100% internal quantum efficiency. Further enhancement included the addition of antireflection (AR) coating. NASA delivered the coated, delta-doped EMCCD for observations at the Palomar observatory and subsequently for flight in the Faint Intergalactic Redshifted Emission Balloon (FIREBALL).



2-D-doped p-channel CCD for future Orion mission, CHESS rocket, and Mount Bigelow observation runs. (Credit: Todd Jones)

**P-channel Charge-coupled Devices (CCDs)** offer high radiation tolerance and are therefore very suitable for space-based applications, including next-generation observatories that will conduct wide-field

imaging surveys to study the formation and survival of stellar and planet-forming environments. Working with collaborators from Lawrence Berkeley National Laboratory, NASA enhanced a broadband p-channel CCD with 2-D doping and custom AR coating for use in the 320-1000-nm range. The new p-channel CCD was provided to Arizona State University for use at the Mount Bigelow observatory and to the Orion program for use in future missions. NASA also delivered a similar CCD enhanced for far UV to the Colorado High-resolution Echelle Stellar Spectrograph (CHESS) sounding rocket.



2-D and AR-coated n-channel CCD with custom packaging for the Palomar WaSP camera. (Credit: Todd Jones)

**N-channel CCDs** that are fabricated in thick, ultra-high purity silicon can be used in applications where broadband response is required. An example of such application is a star formation observatory concept named High Orbit

Ultraviolet-Visible Satellite (HORUS). NASA delivered a broadband n-channel, fully depletable, thick CCD optimized for observations in the NUV to NIR spectrum

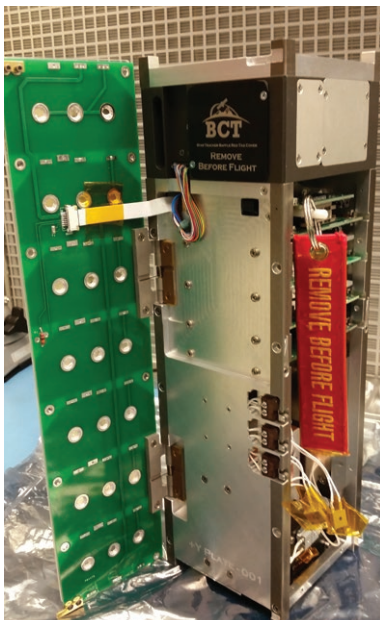
to the Palomar Observatory for use with the WAfer-Scale camera for Prime (WaSP) camera.

**Impact:** Future NASA missions will require high-performance detector arrays. All three of these silicon arrays take advantage of processes developed at NASA to produce high-efficiency arrays with extended response in the ultraviolet and near infrared.

**Status and Future Plans:** The on-sky observations have revealed good performance and the team is continuing to develop and mature this technology. NASA is planning suborbital flights for the p-channel (a sounding rocket experiment) and n-channel EMCCD arrays (a balloon-borne experiment).

**Sponsoring Organization:** The Astrophysics Division supported development of these technologies through the SAT program. Shouleh Nikzad, April Jewell, Timothy Goodsall, Todd Jones, and Michael Hoenk from NASA JPL led these development efforts.

## HIGH-PRECISION POINTING ON A CUBESAT ENABLES NEW SCIENCE



The BCT XACT pointing system (top dark grey box, 0.5 Unit) integrated onto MinXSS-1 (3 Units). Photo credit: CU/LASP.

### Technology Infusion:

A team led by University of Colorado (CU) researchers has successfully developed the first science CubeSat mission for NASA's Heliophysics Division. The Miniature X-ray Solar Spectrometer-1 (MinXSS-1) is a 3-Unit CubeSat measuring the energy distribution of soft X-rays from the sun. The satellite was deployed from the International Space Station on May 16, 2016 and has been

operating for over nine months, as of March 1, 2017. To take measurements, MinXSS-1 must stably point its primary science instrument, an Amptek X123 X-ray

spectrometer, towards the sun. This precise pointing is made possible by the new Blue Canyon Technologies (BCT) XACT attitude determination and control system (ADCS), which experienced its first flight on MinXSS-1. The XACT can continuously point MinXSS-1 to within 0.002° of the sun, which is akin to pointing at the U.S. Capitol Building in Washington DC from Los Angeles, Ca. This new, high level of pointing precision is now commercially available for CubeSat missions and enables scientific measurements that simply were not possible before. Other innovations in the MinXSS-1 mission include measuring the solar X-ray spectrum with unprecedented energy resolution using a Silicon Drift Detector (SDD) in the Amptek X123; technology demonstration of a low-noise, low-power electrometer for photodiodes that was developed for the National Oceanic and Atmospheric Administration's Geostationary Operational Environmental Satellite (GOES) series; and deployable, high-efficiency solar panels designed and built by CU graduate students.

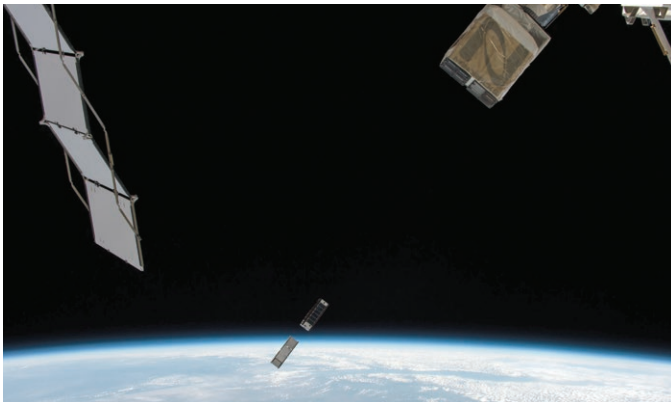
**Impact:** MinXSS-1 was the first science CubeSat launched for SMD. The pointing performance of XACT has already been employed with the solar X-ray measurements obtained by MinXSS-1. The energy resolution of the X123 is about 400 times higher than the resolution the GOES X-Ray Sensor (XRS) has provided for decades. XRS measurements are the standard by which solar flares are classified. Using simultaneous measurements from MinXSS-1 and GOES XRS, researchers have developed a new calibration method for the XRS data that yields a more accurate value for the Sun's soft X-ray emission brightness and the temperature of the solar corona. Future studies of solar flares and many space weather applications will benefit greatly from this new method.

MinXSS-1 data are also being used to study the material flowing upward from the Sun's surface into the corona during solar flares to learn how the corona can be about 2 million degrees Fahrenheit, while the solar surface (photosphere) is only about 10 thousand degrees Fahrenheit, and to determine how magnetic energy on the Sun is driving the intense activity of solar X-rays.

NASA is already one of the biggest consumers of BCT pointing systems. The Agency also flew one on the Earth Science RAVAN mission (see page 6) and plans to fly

them on the Mars Cube One (MarCO) mission to Mars as part of the InSight mission, the Compact Radiation Belt Explorer (CeREs) CubeSat to study Earth's radiation belt, and numerous other missions. The challenge of precision pointing on a CubeSat science mission has now been solved with the BCT ADCS; therefore, NASA and other institutions planning CubeSat missions can now focus on developing compact instruments to advance the science results from future CubeSat missions.

**Status and Future Plans:** In 2016, the BCT XACT system was proven to be a robust ADCS that is providing amazing 0.002° pointing precision for the MinXSS-1 CubeSat. The MinXSS team at the University of Colorado will continue operating MinXSS-1 until its expected re-entry in May 2017. The team has also developed the MinXSS-2 CubeSat, which is ready for launch in 2017 to a higher-altitude Sun-synchronous orbit, where it will operate for five years.

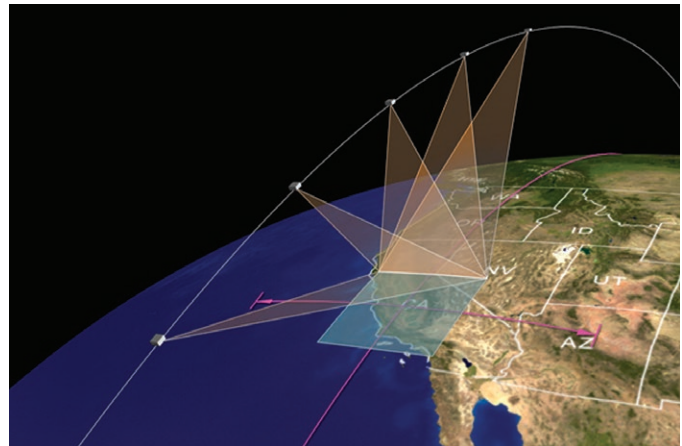


Deployment of NASA MinXSS-1 (lower left CubeSat) and National Science Foundation/University of Michigan CubeSat investigating Atmospheric Density Response to Extreme driving (CADRE) (upper right) from the International Space Station on 2016 May 16. (Credit: Tim Peake, ESA/NASA)

**Sponsoring Organization:** Technology development for MinXSS-1 was funded by the SMD Heliophysics Division H-TIDeS program. The PI is Dr. Thomas N. Woods at the Laboratory for Atmospheric and Space Physics at the University of Colorado in Boulder, and the MinXSS team includes scientists and engineers from University of Colorado, NASA GSFC, Southwest Research Institute, the National Center for Atmospheric Research, and the U.S. Naval Research Laboratory.

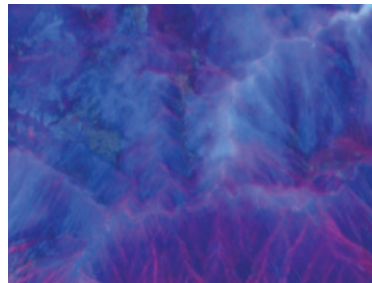
## SMD-SPONSORED TECHNOLOGIES INFUSED INTO THIRD SET OF EARTH VENTURE INSTRUMENTS

**Technology Infusion:** In March 2016, NASA announced the selection of two proposals—both direct infusions of Earth Science Technology Office (ESTO) projects—under the third solicitation of the Earth Venture Instrument (EVI) program. Managed by the Earth System Science Pathfinder (ESSP) program, the EVI program targets emerging instruments for orbital missions of opportunity.



Artist's depiction of MAIA's multi-angle measurement approach. (Credit: NASA JPL)

The **Multi-Angle Imager for Aerosols (MAIA)** will use a twin-camera instrument to make radiometric and polarimetric measurements needed to characterize the sizes, compositions, and quantities of particulate matter (aerosols) in air pollution. MAIA measurements, combined with population health records, could lead



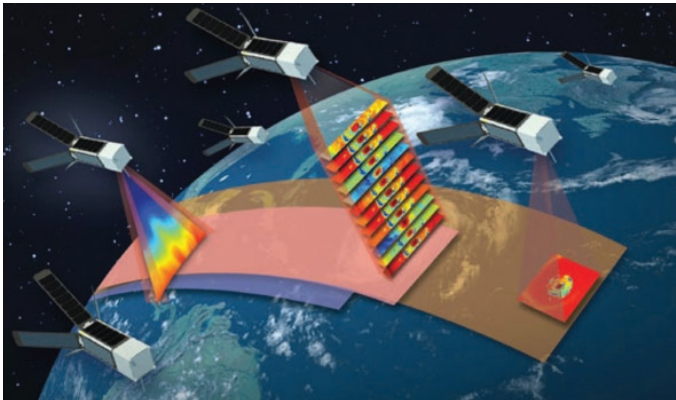
An example of an AirMSPI intensity image, from August 30, 2012 overflight of the Chips wildfire in California. (Credit: D. Diner/JPL)

to a better understanding of connections between aerosol pollutants and health problems—adverse birth outcomes, cardiovascular and respiratory diseases and premature deaths—in the world's

major cities. MAIA will be a direct descendent of the ESTO-funded Airborne Multi-angle Spectropolarimetric Imager (AirMSPI), a UV/VNIR/SWIR (ultraviolet/visible and near-infrared/shortwave-infrared) multi-angle polarimetric

camera that has successfully flown repeatedly on aircraft to measure aerosols and clouds.

The **Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS)** project will develop and launch a constellation of 12 CubeSats to study the development of tropical cyclones through rapid-revisit sampling. TROPICS will use scanning microwave radiometers to measure temperature, humidity, precipitation, and cloud properties. The CubeSats will be launched into three orbital planes to enable monitoring of tropical cyclones with a revisit time of as little as 20 minutes. The TROPICS instrument will benefit from prior microwave receiver technology development, as well as the ESTO-funded Microwave Radiometer Technology Acceleration (MiRaTA) project, a CubeSat under development to space-validate a new microwave radiometer.



Artists depiction of the constellation of TROPICS CubeSats, 12 in all, each about one foot long. (Credit: MIT Lincoln Laboratory)

**Impact:** In addition to providing unprecedented, high-resolution, nearly global measurements that will enable the study of environmental and inner-core conditions for tropical cyclones, TROPICS will serve as a model for future missions by demonstrating that a constellation approach can provide valuable Earth science data at extremely low cost. MAIA will demonstrate new, multi-angle measurements of particulate matter in air pollution that are key to understanding air quality, epidemiology, and public health.

**Status and Future Plans:** Development efforts for MAIA and TROPICS are underway at NASA JPL and MIT, respectively. Launch dates are not yet determined, but may be as soon as 2021.

**Sponsoring Organization:** NASA provided funding to support AirMSPI – the precursor to technology used by MAIA—via ESTO’s Instrument Incubator Program (IIP). The MAIA project is led by PI D. Diner at NASA JPL. Technology development benefitting the TROPICS project, including MiRaTA, was supported via ESTO’s InVEST and ACT programs. W. Blackwell at MIT Lincoln Laboratory is the PI for TROPICS.

# APPENDIX A. THE SMD TECHNOLOGY DEVELOPMENT STRATEGY

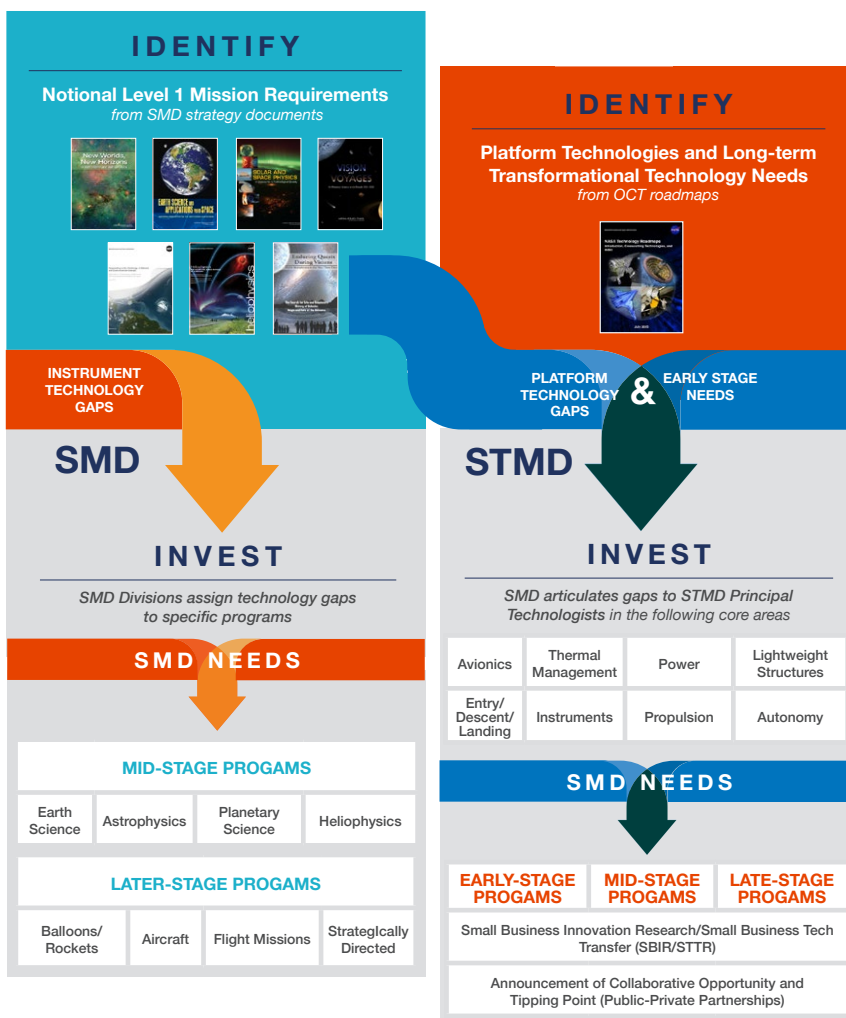
Sustained investment in technology development and infusion of viable new technologies is key to NASA success. The Agency's airborne and in-space flight missions, along with its scientific research and analysis

(R&A) programs, represent the primary customer base for SMD's technology development efforts. Studies have shown that technology readiness is especially important for flight missions because the maturity of a

mission's onboard instruments and space components significantly impacts the cost and risk of the mission<sup>1</sup>. SMD's approach is to mature required technologies years in advance of flight mission implementation, thereby retiring risk, reducing cost, and increasing the likelihood that new technologies will be incorporated into flight projects.

SMD must invest in technology that supports the needs of its four science divisions. NASA's Space Technology Mission Directorate (STMD) is an important SMD partner in this process, particularly for technology development efforts that are applicable Agency-wide. Effective technology development requires careful analysis of technology gaps, identification of technologies to fill those gaps, sustained investment to advance the chosen technologies, and then successful infusion into missions or other products. The diagram to the left depicts the SMD technology development process.

## SMD TECHNOLOGY DEVELOPMENT PROCESS

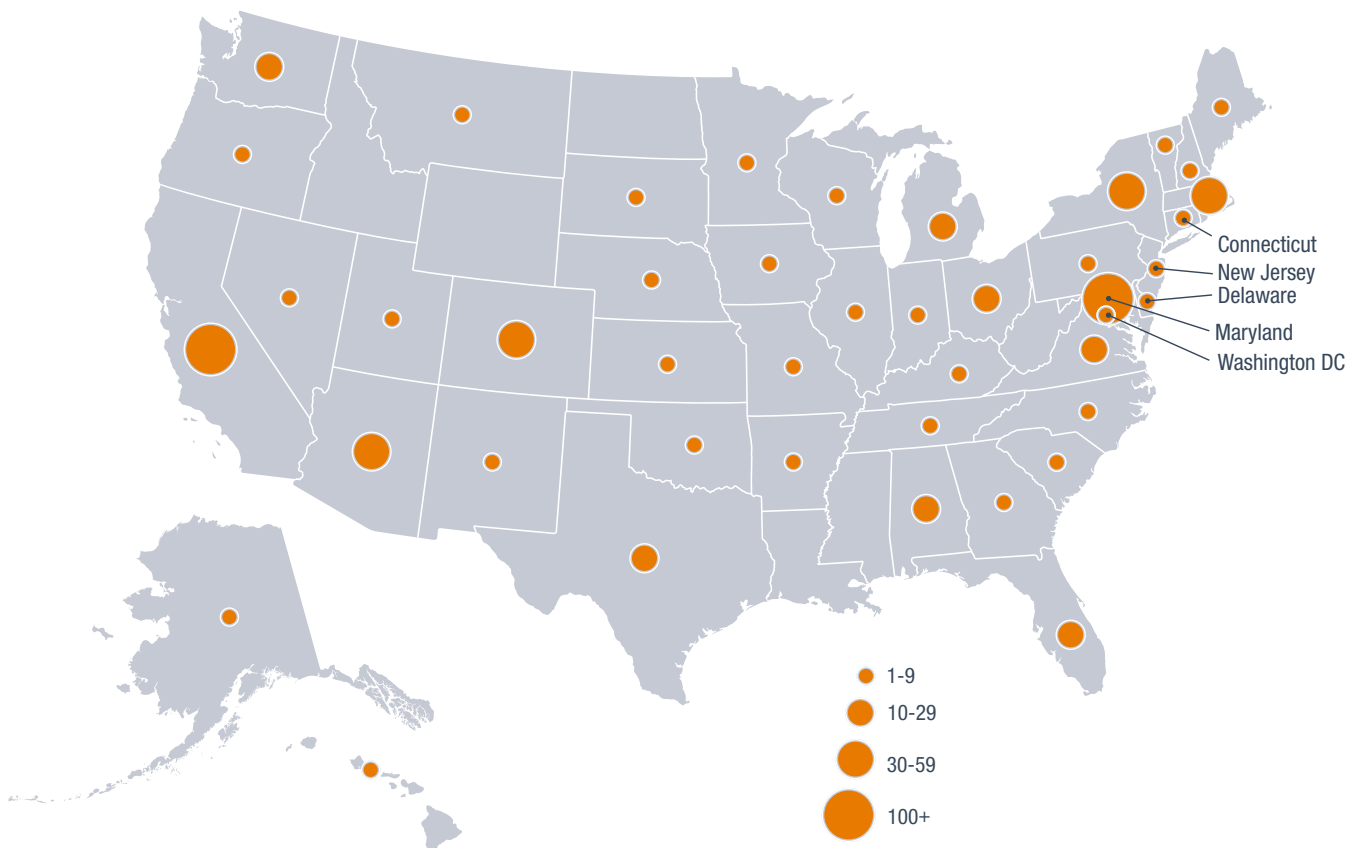


<sup>1</sup>U.S. Government Accountability Office. NASA Assessments of Selected Large-Scale Projects. GAO-12-207SP. Washington, D.C.: U.S. Government Printing Office, 2012. This report concluded that the maturity of instruments and space components impacts the cost and risk of flight missions (i.e., proposed flight missions should include technologies at TRL 6 or greater).

SMD divisions receive guidance from the National Academies' decadal surveys and the science community and 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 need for instruments with new or increased capabilities. Each SMD division accomplishes its technology development via competed opportunities offered through 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. (See the table

on page 4 for a list of division technology development programs.) 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 roadmaps produced by NASA's Office of the Chief Technologist (OCT) to determine if any of the technology needs identified elsewhere in the Agency complement SMD technology needs. Usually these needs concern platform technologies or 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



Distribution of PI and other organizations and institutions participating in SMD technology development efforts active in 2016; the size of the circle corresponds to the number of organizations and institutions receiving funding in each state.



STMD 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.

This report highlights a sample of the activities comprising the broad portfolio of SMD technology projects. In 2016, SMD division technology development programs funded numerous projects distributed throughout the nation (see map on previous page). SMD technology development participants reside at various NASA Centers and at institutions throughout the United States.

## ACRONYMS

<b>AC</b>	Alternating Current	<b>FUV</b>	Far-Ultraviolet
<b>ACT</b>	Advanced Component Technologies	<b>GCD</b>	Game Changing Development
<b>ADCS</b>	Attitude Determination and Control System	<b>GEER</b>	Glenn Extreme Environments Rig
<b>AGB</b>	Asymptotic Giant Branch	<b>GOES</b>	Geostationary Operational Environmental Satellite
<b>AIST</b>	Advanced Information Systems Technology	<b>GOLD</b>	Global-scale Observations of the Limb and Disk
<b>APRA</b>	Astrophysics Research and Analysis	<b>GPS</b>	Global Positioning System
<b>AR</b>	Antireflection	<b>GRC</b>	Glenn Research Center
<b>ASCAT</b>	Advanced SCATterometer	<b>GSFC</b>	Goddard Space Flight Center
<b>BCT</b>	Blue Canyon Technologies	<b>HIRMES</b>	High-Resolution Mid-Infrared Spectrometer
<b>BOL</b>	Beginning of life	<b>HORUS</b>	High Orbit Ultraviolet-Visible Satellite
<b>CAFE</b>	Composite Assisted Funneling of Electrons	<b>HRD</b>	Hurricane Research Division
<b>CAT</b>	Critical-Angle Transmission	<b>ICON</b>	Ionospheric Connection Explorer
<b>CCD</b>	Charge-Coupled Device	<b>IIP</b>	Instrument Incubator Program
<b>CHESS</b>	Colorado High-resolution Echelle Stellar Spectrograph	<b>IMPACT</b>	Institute for Modeling Plasma, Atmospheres and Cosmic Dust
<b>CO2</b>	Carbon dioxide	<b>IMU</b>	Inertial Measurement Unit
<b>CTD</b>	Composite Technology Development	<b>ISM</b>	Interstellar Medium
<b>CU</b>	University of Colorado	<b>ISS</b>	International Space Station
<b>DC</b>	Direct Current	<b>JAXA</b>	Japan Aerospace Exploration Agency
<b>EMCCD</b>	Electron-multiplying Charge-coupled Device	<b>JPL</b>	Jet Propulsion Laboratory
<b>eMMRTG</b>	Enhanced Multi-Mission Radioisotope Thermoelectric Generator	<b>LLISSE</b>	Long-Life In-Situ Solar System Explorer
<b>ESSP</b>	Earth System Science Pathfinder	<b>LUVOIR</b>	Large Ultraviolet/Optical/Infrared
<b>ESTO</b>	Earth Science Technology Office	<b>MAIA</b>	Multi-Angle Imager for Aerosols
<b>EVI</b>	Earth Venture Instrument	<b>MIT</b>	Massachusetts Institute of Technology
<b>FIREBALL</b>	Faint Intergalactic Redshifted Emission Balloon	<b>MMRTG</b>	Multi-Mission Radioisotope Thermoelectric Generator

<b>NESSF</b>	NASA Earth and Space Science Fellowship	<b>SRON</b>	The Netherlands Institute for Space Research
<b>NIR</b>	Near Infrared	<b>SSERVI</b>	System Exploration Research Virtual Institute
<b>NOAA</b>	National Oceanic and Atmospheric Administration	<b>STMD</b>	Space Technology Mission Directorate
<b>NUV</b>	Near UV	<b>SWIR</b>	Shortwave-infrared
<b>OGE</b>	Office of the Chief Engineer	<b>SXS</b>	Soft X-ray Spectrometer
<b>OCT</b>	Office of the Chief Technologist	<b>TCIS</b>	Tropical Cyclone Information System
<b>OSU</b>	Ohio State University	<b>TCOR</b>	Technology Development for Cosmic Origins Program
<b>PCB</b>	Printed Circuit Board	<b>TDC</b>	Technology Demonstration Convertors
<b>PI</b>	Principal Investigator	<b>TDEM</b>	Technology Development for Exo-Planet Missions
<b>PICASSO</b>	Planetary Instrument Concepts for the Advancements of Solar System Observations	<b>TE</b>	Thermoelectric
<b>PSD</b>	Planetary Science Division	<b>TES</b>	Transition Edge Sensor
<b>PSTAR</b>	Planetary Science Technology Through Analog Research	<b>TLS</b>	TeraHertz Limb Sounder
<b>R</b>	Resolving power	<b>TPCOS</b>	Technology Development for Physics of The Cosmos
<b>R&amp;A</b>	Research and Analysis	<b>TRL</b>	Technology Readiness Level
<b>RAVAN</b>	Radiometer Assessment using Vertically Aligned Nanotubes	<b>TROPICS</b>	Time-Resolved Observations of Precipitation Structure and Storm Intensity with a Constellation of Smallsats
<b>RPS</b>	Radioisotope Power Systems	<b>TTDP</b>	Thermoelectric Technology Development Project
<b>RPSP</b>	Radioisotope Power System Program	<b>U.S.</b>	United States
<b>RTG</b>	Radioisotope Thermoelectric Generator	<b>UM</b>	University of Michigan
<b>SAT</b>	Strategic Astrophysics Technology	<b>UV</b>	Ultraviolet
<b>SBIR</b>	Small Business Innovation Research	<b>UWBRAD</b>	Ultrawideband Software-Defined Microwave Radiometer
<b>SDD</b>	Silicon Drift Detector	<b>VACNT</b>	Vertically Aligned Carbon Nanotubes
<b>SKD</b>	Skutterudite	<b>VNIR</b>	Visible and near-infrared
<b>SMD</b>	Science Mission Directorate	<b>X-IFU</b>	X-ray Integral Field Unit
<b>SOFIA</b>	Stratospheric Observatory for Infrared Astronomy	<b>XRS</b>	X-Ray Sensor

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