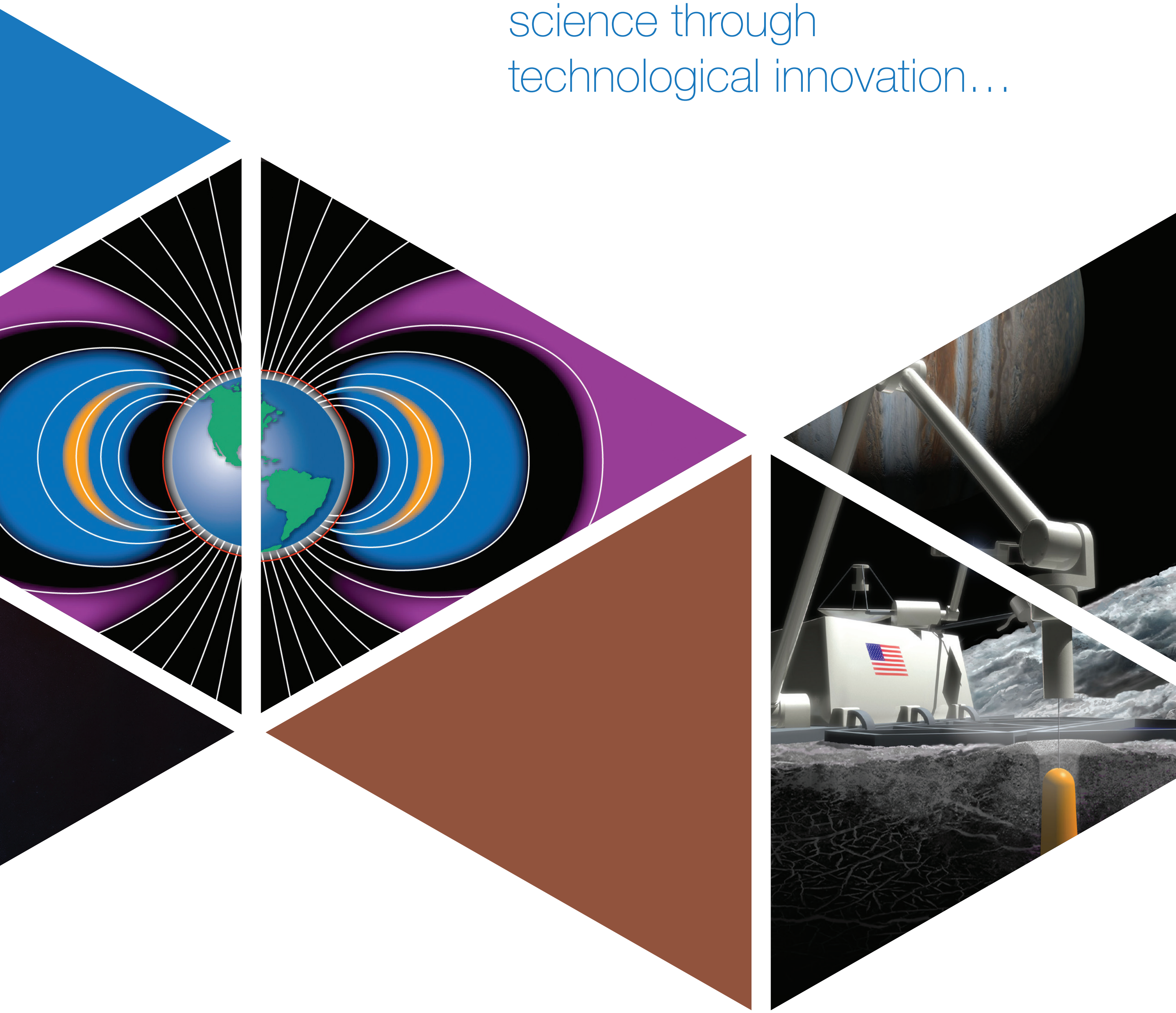
National Aeronautics
and Space Administration

2017

SCIENCE MISSION DIRECTORATE

TECHNOLOGY HIGHLIGHTS

Enabling groundbreaking science through technological innovation…



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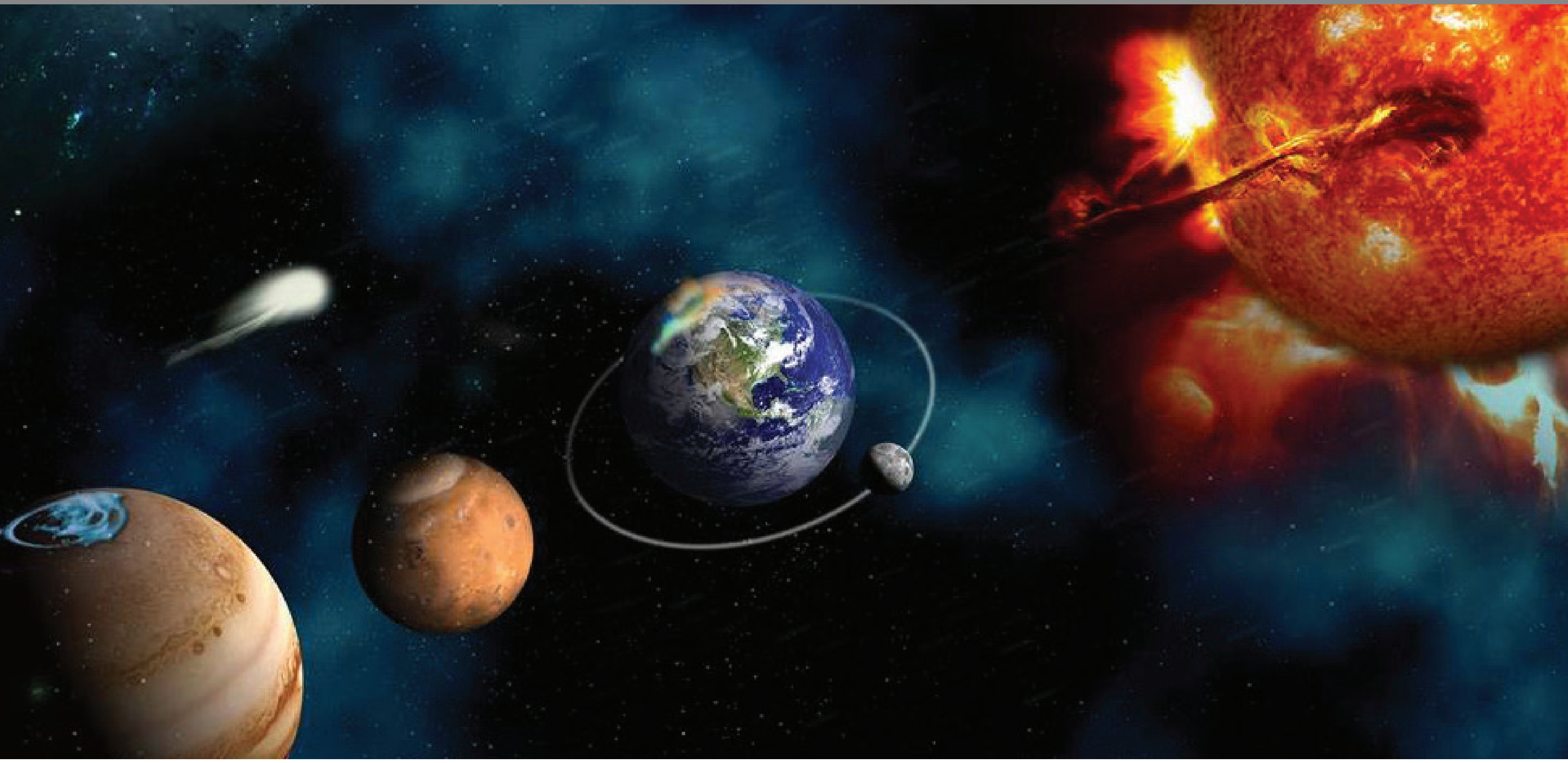


NASA Science Mission Directorate technology investments enable Agency science endeavors that explore Earth systems, the Sun, our solar system, and beyond.

Introduction

Which stars host extrasolar planets, and could those planets harbor life? How did the planets in our solar system evolve, and what can that understanding tell us about Earth? What drives events like solar flares and coronal mass ejections, and how do these events affect our planet? How do Earth systems like the atmosphere, hydrosphere, and biosphere interact, and can we improve climate, weather, and natural hazard predictions?

To answer these and other important questions and to achieve NASA's science vision, the Science Mission Directorate (SMD) sponsors numerous cutting-edge research programs and complementary missions that enable 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.

NASA's Definition of Technology:
A solution that arises from applying the discipline of engineering science to synthesize a device, process, or subsystem to enable a specific capability.[1]

SMD works to ensure that NASA actively identifies and invests in the right technologies at the right time to enable the Agency's science program. Each of the directorate's four science divisions—Astrophysics, Earth Science, Heliophysics, and Planetary Science—develops a focused science program using Agency goals and guidance from the science community (e.g., the recommendations set forth in the decadal surveys produced by the National Academies of Science, Engineering and Medicine) as input. Not only does SMD ensure its technology investments support these division science programs, the directorate coordinates with the NASA Chief Technologist and other Agency mission directorates

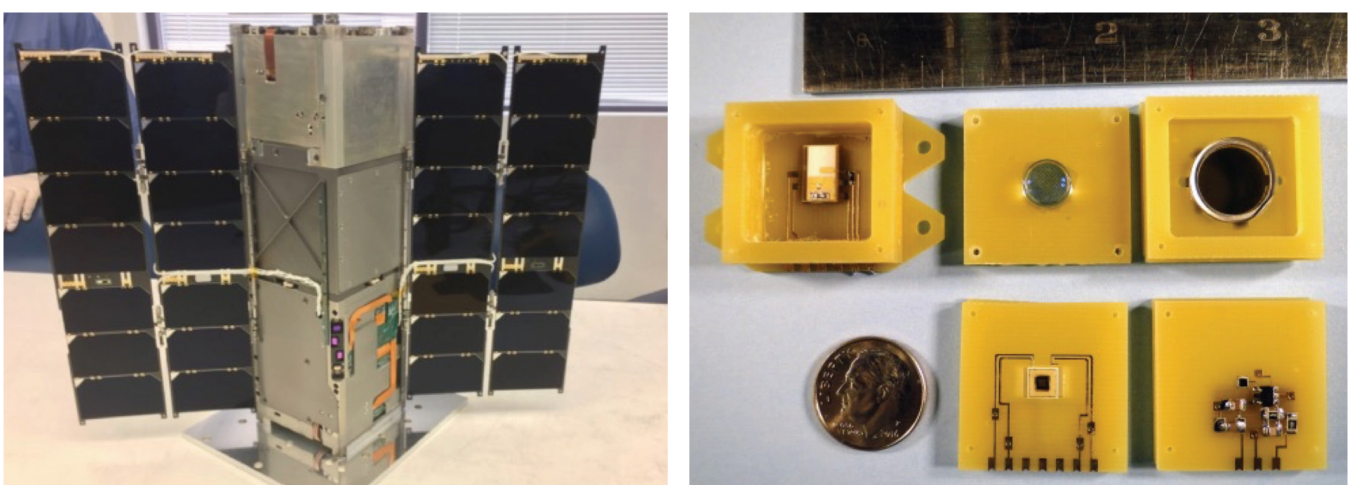
[1] NASA Strategic Technology Investment Plan 2017 (available online at https://www.nasa.gov/offices/oct/home/sstip.html)

to ensure SMD contributes to and benefits from the comprehensive Agency-wide technology strategy. 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.

Small spacecraft platforms, which can be deployed via rockets, other satellites, and the International Space Station, are helping NASA advance scientific and human exploration, reduce the cost of new space missions, and expand access to space.

For example, several of the SMD technology investments profiled in this report are contributing to an Agency-wide effort to enable small satellite capabilities. Small spacecraft platforms—from CubeSats that can be as small as 10 cm^3 to small satellites up to about 1 m^3—often employ commercial off-the-shelf components, generally require shorter development time, and can often be less expensive than larger space missions. Small satellite missions not only provide a cost-effective way to demonstrate new technologies, they could potentially allow the Agency to conduct enhanced science missions, such as flying swarms of tiny spacecraft to gather simultaneous, multi-point observations. However, these small spacecraft require instruments and navigation, propulsion, and communication systems that can accommodate limited size, weight, and power constraints. Many SMD technology investments, such as CubeSat demonstrations and development of miniaturized instruments, are helping NASA address these technology gaps to enable small satellite missions.

SMD accomplishes technology development through technology programs established in each of its four science divisions. (See table on page 5 for a list of SMD technology development programs.)



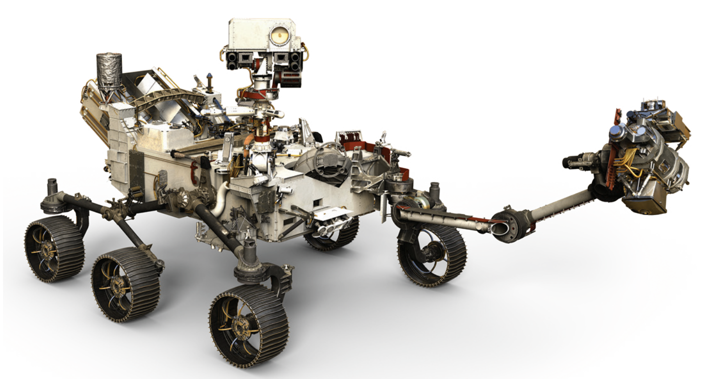
SMD is sponsoring several technology development efforts to enable and demonstrate small satellites, including the Radiometer Assessment using Vertically Aligned Nanotubes (RAVAN) CubeSat initiative (left) and development of a miniature magnetometer (right).

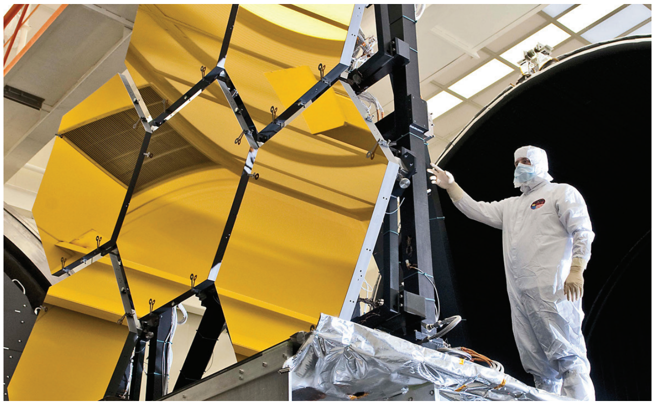
DEFINITIONS OF NASA TECHNOLOGY READINESS LEVELS (TRL)[2]

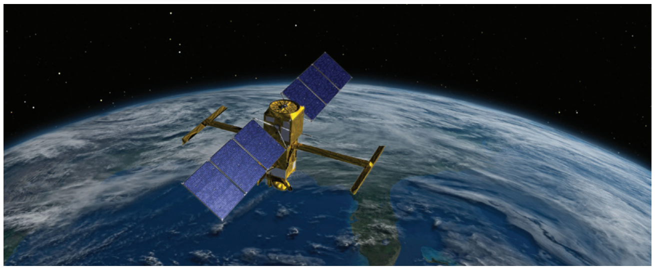
NASA TRL	DEFINITION
1	Basic principles obseerved and reported.
2	Technology concept and/or application formulated.
3	Analytical and experimental critical funtion and/or characteristic proof of concept.
4	Component and/or breadboard validation in laboratory environment.
5	Component and/or breadboard validation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

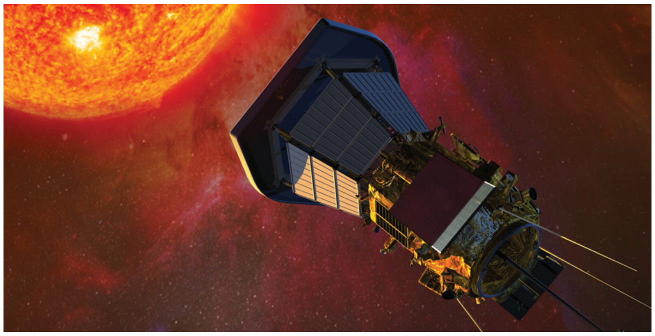
If a technology development effort reaches a NASA Technology Readiness Level (TRL) that is high enough, it may be infused into an SMD flight program and targeted for further maturation, enabling its use for a specific mission application. In some cases, other programs within SMD (e.g., the Astrophysics 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 2017. Chapter two highlights technology achievements that were sponsored by SMD technology development programs in 2017. The third chapter describes highlights from recent SMD technology infusions, and Appendix A briefly details SMD's technology strategy and technology development process, including the coordination between SMD and the NASA Space Technology Mission Directorate (STMD) that ensures SMD technology needs are fulfilled.









SMD technology investments are enabling several upcoming NASA missions. Pictured clockwise from left: the Mars 2020 rover, the first six flight-ready primary mirror segments for the James Webb Space Telescope, the Parker Solar Probe, and the Surface Water and Ocean Topography (SWOT) mission.

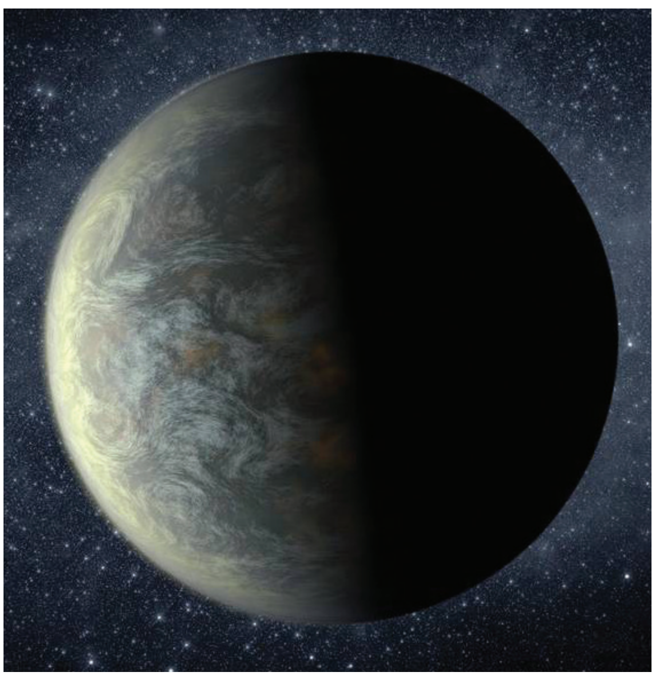
[2] NPR 7123.1B, NASA Systems Engineering Processes and Requirements (available online at https://nodis3.gsfc.nasa.gov)

SMD TECHNOLOGY DEVELOPMENT PROGRAMS

EARTH SCIENCE DIVISION	
Advanced Component Technologies (ACT)	Develops a broad array of components and subsystems for instruments and observing systems.
Instrument Incubator Program (IIP)	Funds innovative technologies leading directly to new Earth observing instruments, sensors, and systems.
Advanced Information Systems Technology (AIST)	Develops tools and techniques to acquire, process, access, visualize, and otherwise communicate Earth science data.
In-Space Validation of Earth Science Technologies (InVEST)	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	
Sounding Rockets and Range Program	Develops new sounding rocket and range technologies; serves as a low-cost testbed for new scientific techniques, scientific instrumentation, and spacecraft technology eventually flown on satellite missions.
Heliophysics Technology and Instrument Development for Science (H-TIDeS)	Supports basic research 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	
Planetary Instrument Concepts for the Advancement of Solar System Observations (PICASSO)	Funds the development of low-TRL technologies (TRL 1-3) leading directly to the development of new Planetary Science observing instruments, sensors and in situ systems.
Maturation of Instruments for Solar System Exploration (MatISSE)	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.
Concepts for Ocean Worlds Life Detection Technology (COLDTech)	Supports the development of spacecraft-based instruments and technology for surface and subsurface exploration of ocean worlds such as Europa, Enceladus, and Titan.
Hot Operating Temperature Technology Program (HOTTech)	Supports the development of technologies for the robotic exploration of high-temperature environments, such as the Venus surface, Mercury, or the deep atmosphere of Gas Giants.
Radioisotope Power System Program (RPSP)	Strategically invests in nuclear power technologies to maintain NASA's current space science capabilities and enable future space exploration missions.
ASTROPHYSICS DIVISION	
Astrophysics Research and Analysis (APRA)	Supports basic research of new technologies (TRL 1-3) and feasibility demonstrations that may enable future science missions. Also supports science investigations through suborbital flights that often involve a significant level of technology development.
Strategic Astrophysics Technology (SAT)	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).
Roman Technology Fellowships (RTF)	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 Developments

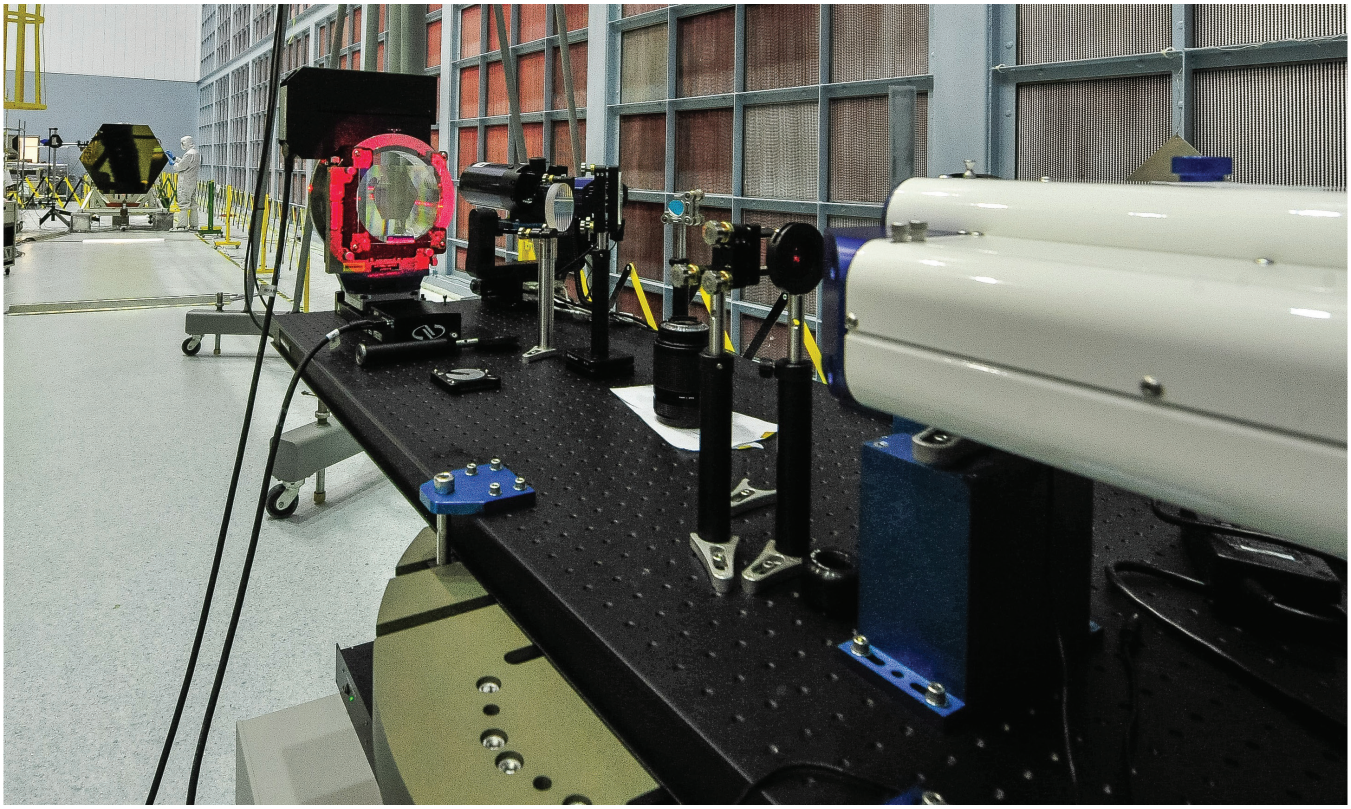
RECORD-SETTING DISPLACEMENT MEASUREMENTS TO ENABLE THE SEARCH FOR DISTANT LIFE



Development of an ultra-stable observatory to detect and study exoplanets such as the one in the artists rendition shown above requires the capability to measure subatomic-sized distortions. (Image credit: NASA/Ames/JPL-Caltech)

Technology Development: A team of NASA optics experts has built a picometer spatial metrology system that may enable a major Agency initiative—to locate and image Earth-like planets beyond the solar system and scrutinize their atmospheres for signs of life. Researchers at Goddard Space Flight Center (GSFC), in conjunction with collaborators at the Space Telescope Science Institute in Baltimore, have demonstrated for the first time the ability to dynamically detect subatomic-sized distortions—changes that are far smaller than an atom—across a five-foot segmented telescope mirror and its support structure.

To detect life on a distant planet, an observatory would have to gather and focus enough light to distinguish the planet's light from that of its much brighter parent star and then be able to dissect that light to discern different atmospheric chemical signatures, such as oxygen and methane. These tasks would require a super-stable, spaceborne observatory whose optical components move or distort no more than 12 picometers—which is about one-tenth the diameter of a hydrogen atom. NASA has not yet built an observatory that meets these demanding stability requirements, and design and implementation of such a stable telescope will require the capability to detect and measure extremely small displacements and movements.



The optical elements in the HSI test setup, including the test mirror segment (hexagonal mirror on the far left).

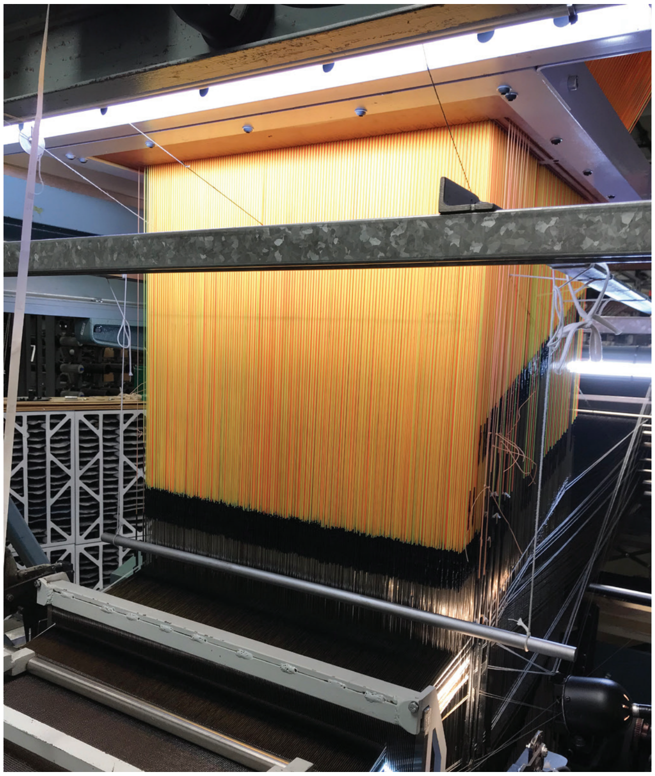
In 2017, the GSFC team used the High-Speed Interferometer (HSI)—an instrument developed by Arizona-based 4D Technology—to measure nanometer-sized dynamic changes in a spare, five-foot mirror segment built for the James Webb Space Telescope (JWST). The test segment included 18 mirror segments, mounts, and supporting structure and the team measured displacements that occurred during thermal, vibration, and other types of environmental testing. Although HSI was designed to measure nanometer- or molecule-sized distortions (the design standard for JWST) the team developed special algorithms that enabled HSI to successfully detect dynamic movement as small as 25 picometers—about half of the desired 12-picometer accuracy.

Impact: The ability to measure such small-scale displacements may enable a future mission (e.g., the Large Ultraviolet/Optical/Infrared Surveyor, or LUVOIR) that will use a large-aperture, segmented, spaceborne telescope not only to conduct general ultraviolet-optical infrared astrophysics, but to search for life on Earth-like planets.

Future Plans: NASA continues to advance the capability to detect subatomic displacement; the GSFC team and 4D Technology have designed a new high-speed instrument, called a speckle interferometer, that allows measurements of both reflective and diffuse surfaces at picometer accuracies. Researchers at GSFC have begun initial characterization of the instrument's performance in a thermal-vacuum test chamber to determine if they can achieve the 12-picometer target accuracy. The team is also evaluating other technologies to relax the requirements so that mission designers do not have to accommodate picometer-level constraints.

Sponsoring Organization: The SMD Astrophysics Division is providing funding for this technology development to Principal Investigator (PI) Babak Saif at NASA GSFC via the SAT program.

HEATSHIELD FOR EXTREME ENTRY ENVIRONMENT TECHNOLOGY NEARS MATURITY

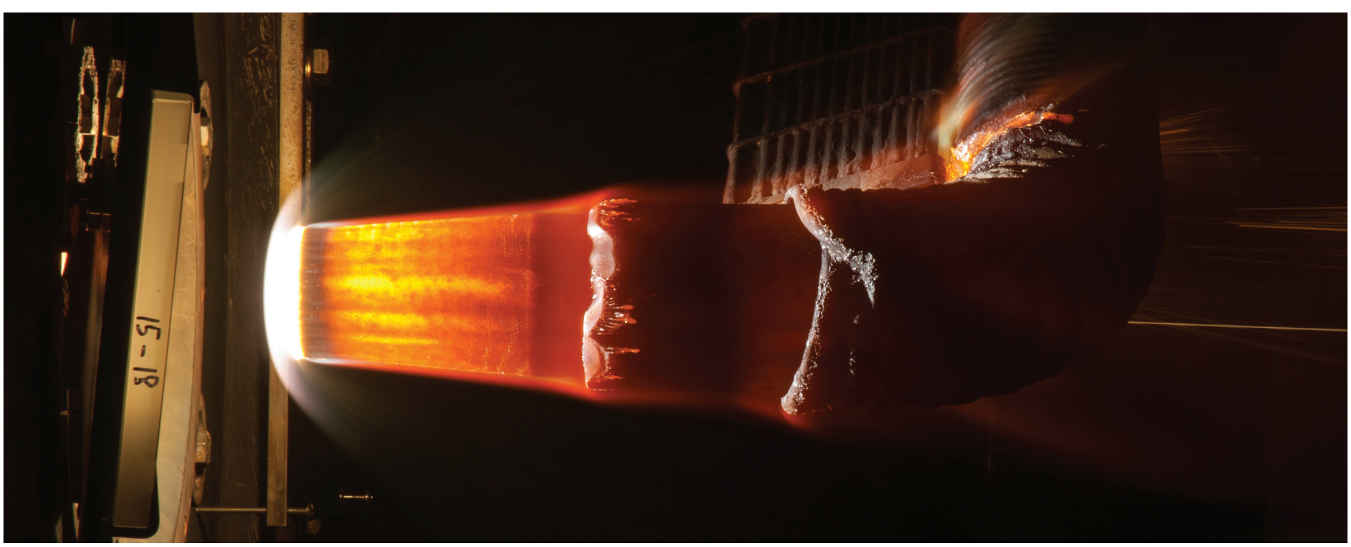


The HEEET material 3-D weaving process

Technology Development: Over the past four years, NASA's Heatshield for Extreme Entry Environment Technology (HEEET) Project has been maturing a novel, three-dimensional, woven Thermal Protection System (TPS) technology for science missions recommended in the Planetary Science Decadal Survey. These missions—Venus probes and landers, Saturn and Uranus probes, and sample return missions to comets and asteroids—will require protection from intense atmospheric heating to reach their destinations. The off-the-shelf TPS product NASA employed on its previous mission to Venus is no longer available, but the technology resulting from the HEEET Project has resulted in an improved solution.

The dual-layer HEEET TPS architecture consists of a high-density, all-carbon layer designed to be exposed to the extreme environments of entry. A lower-density insulating layer, composed of blended carbon and phenolic yarns, is located below the all-carbon layer and is designed to limit the payload temperature. A layer-to-layer weave mechanically interlocks the two layers together.

Because the thickness of the layers can vary, the dual-layer approach results in the ability to optimize the mass for a given mission and provides for greater mass efficiency compared to heritage TPS approaches. The resulting HEEET material allows for a compliant, integrated heat shield that provides protection against extreme entry environments.
To date, the HEEET technology has demonstrated exemplary performance when subjected to arcjet test conditions of 5000 W/cm^2 heat flux and 5 atmospheres of pressure.



HEEET model during arcjet testing at NASA Ames Research Center.

Impact: In addition to filling the TPS technology gap, HEEET will enable extended future mission capabilities. Due to the inherent properties of the heritage TPS material, previous missions had to be designed to withstand high gravitational loads upon entry, limiting the scientific instrumentation that could be utilized. HEEET will provide a mass-efficient and robust solution, allowing missions to be designed with reduced entry loads and a 30% - 40% lower heat shield mass.

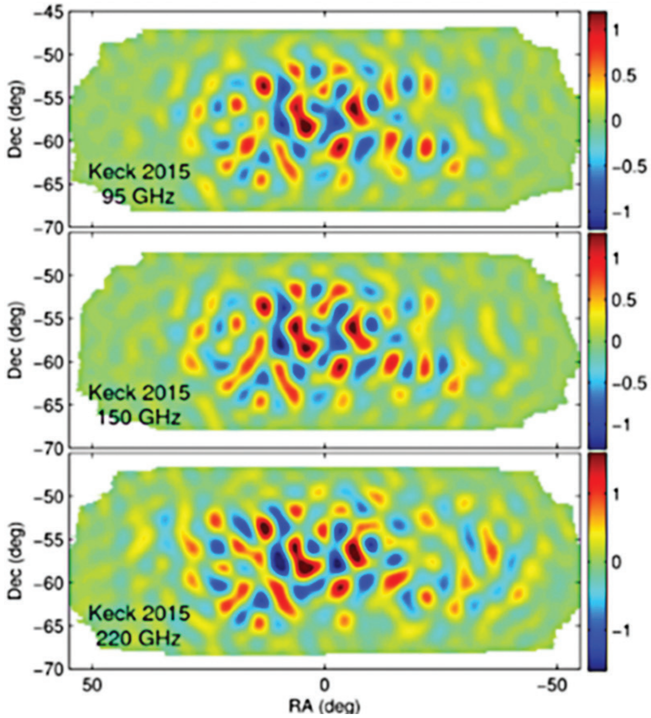
HEEET Engineering Test Unit (ETU) prior to final surface machining

Future Plans: The ongoing HEEET technology development effort will result in a TRL 6 technology for NASA's future planetary and sample return missions. The weaving, molding, and resin infusion aspects of the technology have been transferred to industry and the vendors are ready to support future missions. As part of HEEET's TRL advancement, the project is building a 1-meter diameter Engineering Test Unit (ETU). The ETU interfaces and testing conditions were developed with support from previous flight projects and missions.

Sponsoring Organization: NASA's Space Technology Mission Directorate's Game Changing Development Program and SMD's Planetary Science Division are jointly funding the development of HEEET.

PROBING THE BIRTH OF THE UNIVERSE WITH LARGE-FORMAT DETECTOR ARRAYS

Technology Development: Precise polarization measurements of the Cosmic Microwave Background (CMB) radiation, an ancient glow from the early universe, may help scientists better understand how the universe rapidly expanded in a burst called "inflation" moments after the Big Bang. NASA is developing ultra-sensitive detector arrays to make highly sensitive polarization measurements in a search for a faint polarization pattern caused by gravitational waves produced during inflation. This technology will result in instruments that not only provide improved polarization measurements, but can be deployed on space-based missions, enabling collection of this data across the entire sky.



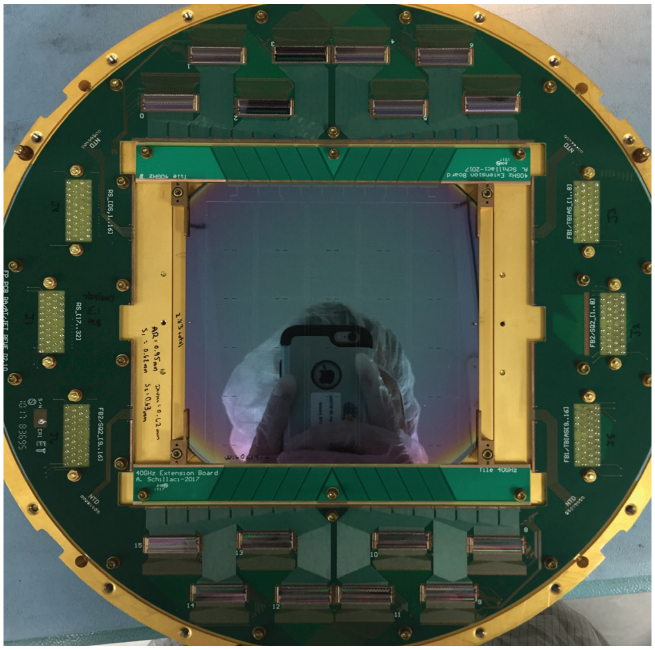
High-sensitivity maps of CMB polarization made at three frequencies by the ground-based BICEP-Keck collaboration. The maps show tiny variations in the polarized signal at a level of +/- 1 micro Kelvin, clearly detected at all three frequencies. These maps have a sensitivity of 50 nK in a square degree at 150 GHz, but only cover a small patch of sky. A future NASA space mission called the Inflation Probe can use the new detector technology to make even more sensitive measurements over the entire sky.

The new technology uses superconducting antennas to gather polarized millimeter-wave radiation with high efficiency. The antennas are flat so they can be made into large-format arrays using photolithography methods. The radiation gathered by each antenna is dissipated as heat on a sensitive transition-edge superconducting bolometer, which has been cooled to a few tenths of a degree above absolute zero to minimize thermal noise. Changes in collected radiation produce small heat variations in the bolometer, which are in turn measured with multiplexed superconducting amplifiers. A key aspect to the technology is the ability to scale the design to operate at a number of wavelengths in modular units, so that researchers can build a large focal-plane array for deployment on future space missions. Multi-frequency measurements are necessary to separate signals from the CMB from sources of emission in our own galaxy.

In 2017, the team extended this technology to larger wafer sizes, roughly doubling the number of detectors that fit in a sub-array. They also developed a new design for operating at lower frequencies, fabricating the first array of this type for observations at 40 GHz. In parallel, the team is developing a modular housing that enables construction of large focal planes made from multiple "sub-array" wafers.

Impact: Demonstrations of these detector arrays from high-altitude ground-based sites and sub-orbital balloons will ready the technology for use in future space missions. Recently published, precise measurements of the CMB in three frequency bands (95, 150, and 220 GHz) obtained using these arrays provide the tightest constraints to date on a polarization pattern from inflation. New arrays developed by the team are now operating at 270 GHz for the first time, which promises further improvements.

Future Plans: Further advances are on the way, using a 150-mm wafer to develop larger array formats. The researchers expect ground and sub-orbital observations using the low-frequency 40-GHz arrays to begin in a couple of years to better measure galactic foregrounds. Since the detectors take up more focal-plane real estate at lower frequencies, the team is developing a dual-color design to squeeze two bands and two polarizations into a single antenna.



The first detector antenna-coupled, transition-edge superconducting arrays developed for 40 GHz on 150-mm diameter wafers for larger formats. The array is shown mounted in a test focal-plane assembly.

Sponsoring Organization: Development of the antenna-coupled, transition-edge superconducting bolometer array is supported by the Astrophysics Division's SAT program through a grant to Dr. James Bock at the Jet Propulsion Laboratory (JPL). The detectors are fabricated at JPL's Micro Devices Laboratory and tested in collaboration with the California Institute of Technology and the University of Illinois.

BEAMSTEERABLE CIRCUIT TO EXPAND RADIO OCCULTATION MEASUREMENT CAPABILITIES

Technology Development: An SMD-sponsored project successfully designed, fabricated, and tested a new application-specific integrated circuit (ASIC) intended to enable high-quality radio occultation (RO) weather observations using signals from the Global Navigation System Satellite (GNSS) constellations. RO measurements are made when a satellite receives the radio transmissions from GNSS satellites through the limb of the atmosphere. Information about atmospheric temperature, pressure, and water content can be derived from the refraction of the GNSS signal as it passes through the atmosphere.

The large circuit board on the left is a previous ASIC design. The three rectangular segments provide three antenna inputs, supporting four 20-MHz channels, and require approximately 5 W of power. To the right is the new ASIC chip. By adding a few small components, such as connectors, it will provide three antenna inputs, with the equivalent of twelve 40-MHz channels, and require only 1 W of power. (Image Credit: Michael Shaw, GigOptics, Inc.)

The new design supports four radio frequency (RF) inputs capable of receiving three GNSS signals per input in a single ASIC, allowing reception of all known GNSS networks worldwide. Multiple RF channels on a GNSS receiver is a unique feature that could also enable precision beamforming. Large beamforming arrays may provide the necessary signal-to-noise ratio to produce ocean altimetry and scatterometry observations.

To verify its performance, the project team integrated and tested the ASIC chip using a simulator and a beamsteerable antenna. During testing, they found the group delay and phase stability to be an order of magnitude better than current receivers. This technology advanced to TRL 4 in 2017, from an initial TRL of 2 when the project began in 2015.

Impact: These small, low-power ASICs will be easier to accommodate on missions of opportunity than current technologies, and could enable constellations of small satellites that provide more frequent coverage and improve weather prediction.

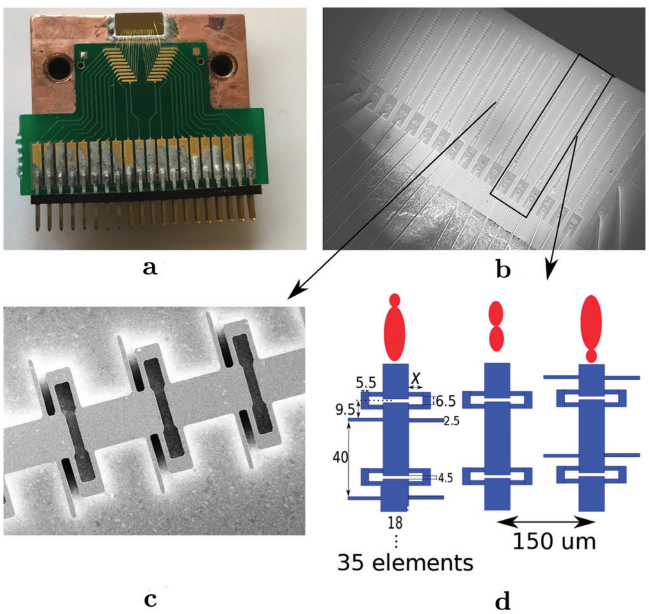
Future Plans: NASA is infusing this new ASIC into a prototype multi-static radar instrument for remote sensing. This new instrument concept targets a low-cost mission to study wetland dynamics and soil moisture content using forward-scattered GNSS signals.

Sponsoring Organization: The Earth Science Division's ACT program funded the development of the Beamsteerable Circuit to Expand Radio Occultation Measurement Capabilities. The Principal Investigator is Michael Shaw of GigOptix, Inc.

ADVANCING LOCAL TERAHERTZ OSCILLATORS TO ENABLE COSMIC OBSERVATIONS

Technology Development: NASA is developing a new type of detector that will provide insight into the formation and structure of the universe. Many of the radiative and mechanical interactions that shape the interstellar medium of galaxies and drive galactic evolution (e.g., shock waves from stellar winds and jets, supernova explosions, etc.) are best observed in the 4.744 terahertz (THz) spectral region for the oxygen line. Observations of this spectral line have rarely been performed, however, because the 4.744-THz frequency is beyond the reach of most existing local oscillators that operate in heterodyne receivers sensitive enough to make such observations. A NASA-sponsored team at Massachusetts Institute of Technology (MIT) is working to advance technologies that will enable upcoming NASA missions to include receivers that observe this important spectral line.

Heterodyne detection compares the incoming light signal with a reference light from a local oscillator (LO). Key challenges of this project are to increase the LO output power from the currently achievable level of <1 mW to 5 mW, and to increase the operating temperature from a lab-demonstrated ~10 K to ~40 K—a temperature that can be accommodated by a space-based or suborbital observatory. To achieve these objectives, the project team is developing local oscillators based on THz quantum-cascade lasers (QCL), which can pump a seven-element heterodyne receiver array. These local oscillators must emit single-frequency radiation with good spectral purity (narrow linewidth <1 MHz at 4.7 THz), which can only be achieved using Distributed-FeedBack (DFB) grating structures. The team investigated three different DFB structures for potential use in the receiver and selected the best option, which has a unidirectional beam pattern (it only radiates in the forward direction) with high output power levels. A picture of such a structure is shown in the figure below.



The figure above shows: (a) an array of 3rd-order DFB lasers gold wire bonded to an electronic chip, (b) a photo of a fabricated array of DFB triplets, (c) scanning electron microscope image of a DFB device showing three periods, and (d) a schematic of a triplet with the corresponding radiation profile.

Impact: A receiver array capable of observing the 4.744-THz frequency will provide new and unique insights into the interrelationship of stars and gas in a wide range of galactic and extragalactic environments. NASA plans to deploy receivers using this technology on the upcoming GUSTO mission (Galactic/Extragalactic Ultralong-Duration Balloon Spectroscopic Terahertz Observatory), a long-duration balloon payload targeted for launch in 2021. The technology also has potential applications for the upcoming Single Aperture Far-Infrared Observatory (SAFIR) mission, a large cryogenic space telescope envisioned as a follow-on to the Spitzer Space Telescope and the Herschel Space Observatory. In addition to astrophysics, THz QCLs will be useful in a wide range of applications in areas such as security, biochemical sensing, and biomedical imaging.

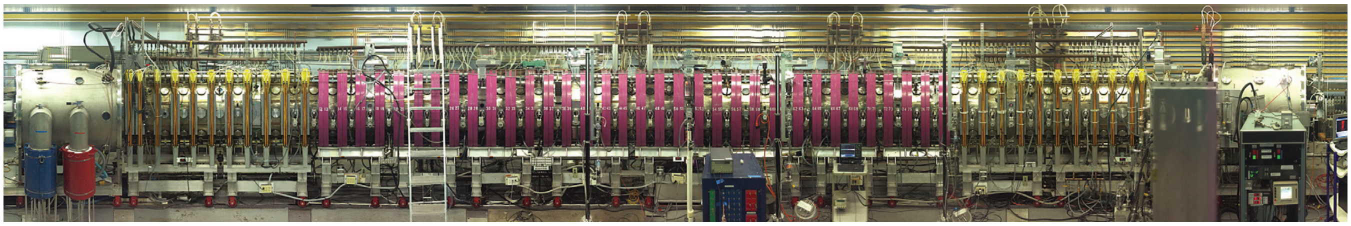
Future Plans: In the near future, the team will develop flight-ready local oscillators for suborbital missions such as GUSTO. In the long term, the work will involve development of local oscillators for space-based observatories such as SAFIR, which will involve devices with even higher performance requirements.

Sponsoring Organization: SMD's Astrophysics Division sponsors this project via the SAT program by providing funding to PI Dr. Qing Hu at MIT.

EXCITING CHIRPING WHISTLER WAVES: FROM THE LABORATORY TO SPACE

Technology Development: Chorus waves are a class of frequency-chirping, whistler-mode plasma waves that are routinely observed in Earth's near-space environment. Chorus waves play a key role in various physical processes including the formation of the Earth's Van Allen radiation belts, the pulsating aurora, and the deposition of particle energy into Earth's upper atmosphere. Although these waves have been observed by satellites for almost six decades, the origin and excitation mechanisms of chorus waves are poorly understood because there are not enough appropriate observations. To observe chorus excitation, it would be necessary to perform high-resolution temporal measurements of three-component electric and magnetic fields simultaneously at a large number of points in space, and be fortunate enough for some of these measurements to occur at the precise location of chorus growth—a nearly impossible feat.

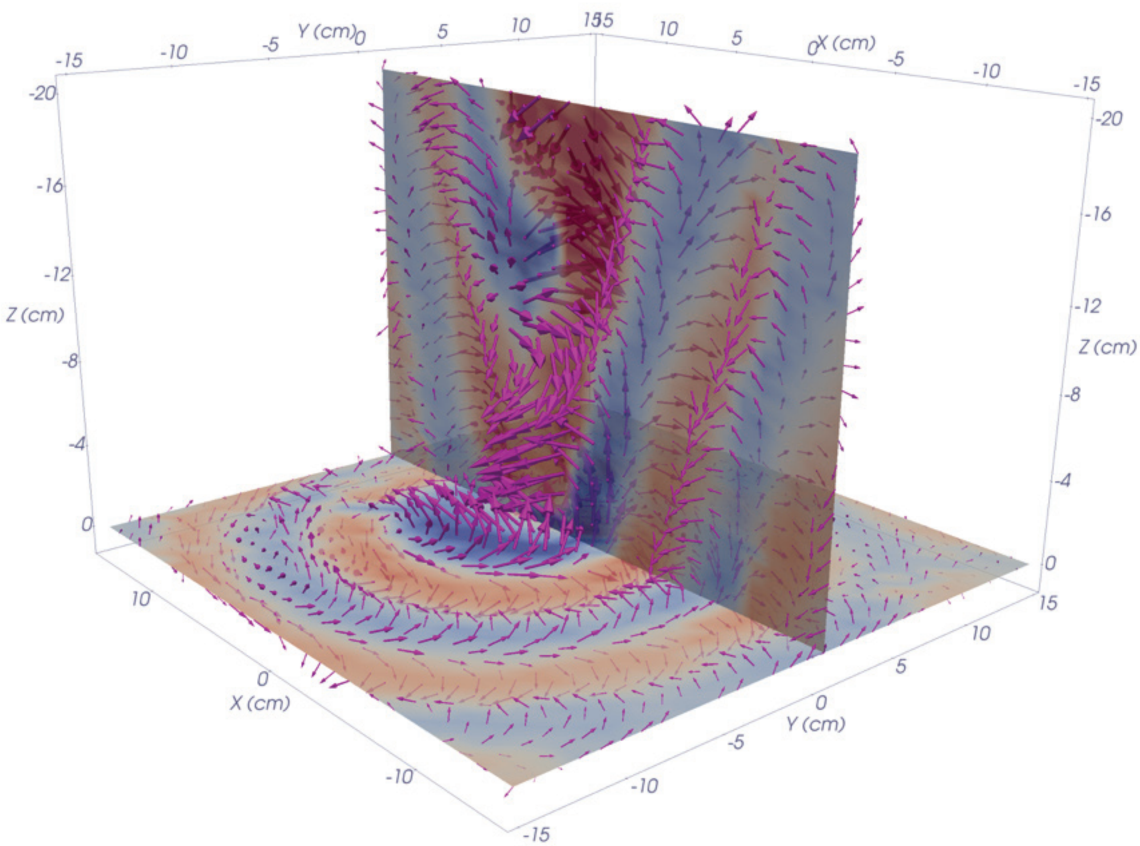
However, using available plasma technology and the enormous capacity for reproducibility and observability in the laboratory, it is possible to excite chorus-like waves at a precise location and use precision instrumentation to perform planar and volumetric imaging of the chorus waves as a function of time. Essentially, researchers can capture data at the very moments that electrons group together



The Large Plasma Device at the University of California, Los Angeles, where whistler waves are studied

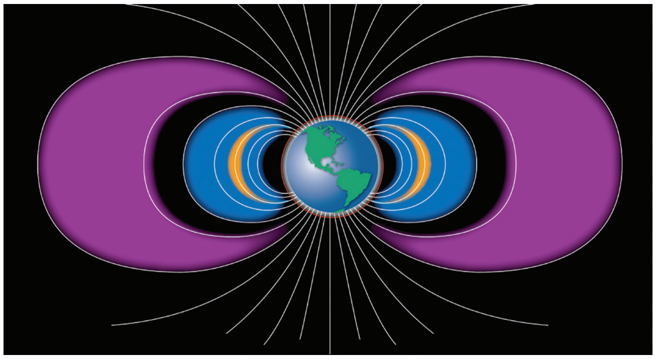
and begin to radiate electromagnetic power within a plasma. A team at the University of California, Los Angeles (UCLA) Large Plasma Device (LAPD) laboratory has developed the appropriate laboratory equipment to excite and image chorus wave growth, while simultaneously developing the numerical simulation tools to understand these observations. In 2017, the team used information gleaned from laboratory observations to develop predictions that were compared against chorus observations obtained by NASA’s Van Allen Probes mission in space. The data from space showed consistent amplitudes to those predicted, validating these new laboratory techniques.

Impact: This knowledge about whistler mode wave excitation, together with the newly developed lab technology, will immediately impact the understanding of the physical processes in which chorus waves are involved (e.g., radiation belts, pulsating and diffuse aurorae). Researchers will be able to apply this knowledge to existing missions like the Van Allen Probes, whose primary objective is to understand radiation belt dynamics. This technology will also enable mankind to create whistler mode waves that can potentially mitigate the damaging effects of high radiation fluxes that can occur either naturally (due to solar processes) or from an attack on U.S. space assets by rogue nations.



Volumetric imaging of excited whistler-mode plasma waves observed in the LAPD at UCLA. The image is built from thousands of individual wave excitation experiments, where data is collected by a single servo-controlled probe that is moved slightly in each experiment. This image is one frame of an animation that shows how the wave is excited and propagates away from its source region.

Future Plans: Next, the team plans to extend laboratory experiments to try and perform "triggered emission" experiments, where weak waves are injected into the system to determine if the free energy in the plasma will nonlinearly amplify them. Similar experiments were performed by the U.S. from Antarctica in the late 1970s.

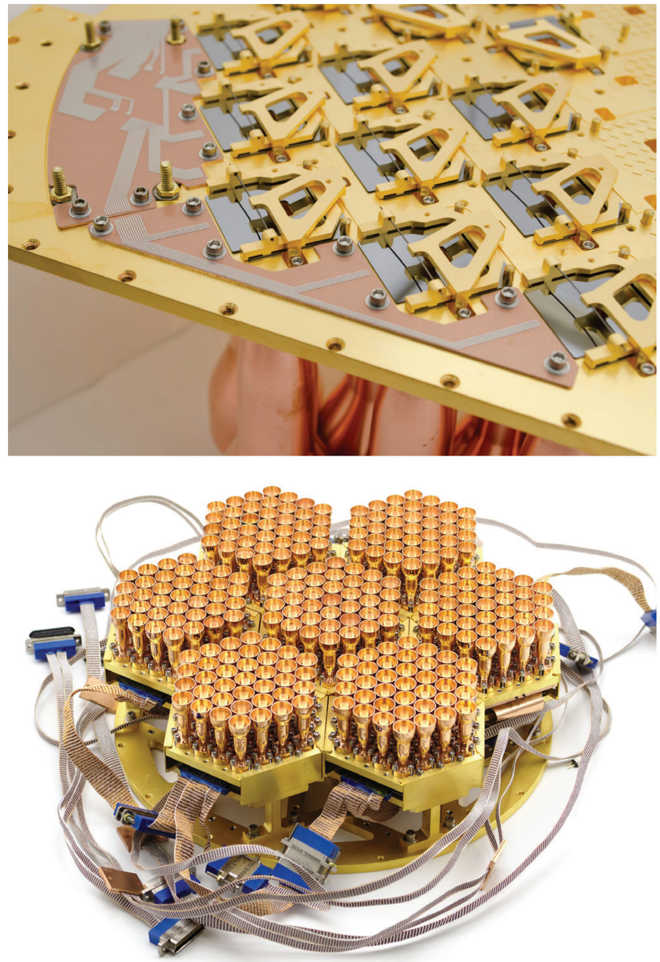


Newly gained knowledge about whistler mode waves will enable research about phenomena like the Van Allen radiation belts surrounding our planet, which are depicted in this artist's rendition.

Sponsoring Organization: This work was sponsored by NASA SMD's Heliophysics Division through the H-TIDeS program, with Prof. Jacob Bortnik as the UCLA PI.

TRANSITION-EDGE SENSOR DETECTORS TO ENABLE CHARACTERIZATION OF THE COSMIC MICROWAVE BACKGROUND

Technology Development: Relic radiation from the Big Bang—the Cosmic Microwave Background (CMB)—provides a Rosetta stone for deciphering the content, structure, and evolution of the early universe. Current theoretical understanding suggests that the universe underwent a rapid exponential expansion, called "inflation," in the first fraction of a second. Such an event would result in an observable stochastic background of gravitational waves that impresses a faint polarized signature on the CMB. The National Research Council's decadal survey recommended characterization of the CMB as a high-priority science objective, but measurement of the polarization signature is very difficult because it is so faint—about 10^{-8} of the 2.725 K isotropic component of the CMB.



The 40 GHz focal plane during assembly (top) and a completed 90 GHz focal plane (bottom). Both have been deployed to Chile for observations of the cosmic microwave background.

Not only would a detector need to be highly sensitive to detect these signals, it would also have to distinguish the minute polarized signal from both instrumental effects and other astrophysical sources.

NASA is sponsoring a team led by researchers at GSFC in collaboration with Johns Hopkins University (JHU) to develop detector technologies that will enable these important observations. This capability requires a highly sensitive and stable instrument, measurements in multiple spectral bands for astrophysical foreground removal, control over potential systematic measurement and calibration errors, and the ability to operate in the unique environmental conditions of space. To address these needs, the development team is implementing polarization-sensitive focal-plane arrays that are compatible with the space environment. The detector architecture combines the excellent beam-forming properties of feedhorns with the sensitivity of transition edge sensor (TES) devices. Focal-plane arrays operating at 40 GHz, 90 GHz, and 150/220 GHz are in development. The team's objective is to advance these detectors to a Technology Readiness Level of 6 (model or prototype demonstration in a relevant environment).

In 2017, the team developed and validated critical details of the fabrication processes for 90-GHz detector wafers, and implemented these into production runs of dichroic 150/220-GHz detectors. The TES membrane thermal design was improved in both detector types, decreasing the thermalization time scales, and leading to improved noise performance at low frequencies. Finally, a cryogenic thermal calibration source was developed and validated from ~30-300 GHz for optical-efficiency polarimetric sensors.

Impact: The feedhorn-coupled TES-based detectors developed via this project are an important step toward implementing an instrument that can successfully characterize the CMB with unprecedented sensitivity. In addition to the performance improvements achieved on individual devices, these research efforts are driving the maturation of the processes required to realize large focal planes with improved reliability and yield.

Future Plans: Representative focal-plane arrays will be integrated by JHU into the Cosmology Large Angular Scale Surveyor (CLASS)—an array of microwave telescopes located at a high-altitude site in the Atacama Desert of Chile—to achieve and demonstrate the TRL objectives for this technology. Targeted test structures are planned to investigate the sensors' coupling properties in detail, with an eye toward improved device performance and achieving greater control over key fabrication parameters.

Sponsoring Organization: The development of these feedhorn-coupled TES-based detectors is supported by the NASA SAT program through a grant to Dr. Edward Wollack at GSFC.

The 40 GHz CLASS telescope, shown at the site in Chile, has been taking science data since September 2016. A 90 GHz telescope is currently being deployed and prepared for commissioning.

ARCHIMEDES: A REALLY COOL HIGH IMPACT METHOD FOR EXPLORING DOWN INTO EUROPAN SUBSURFACE

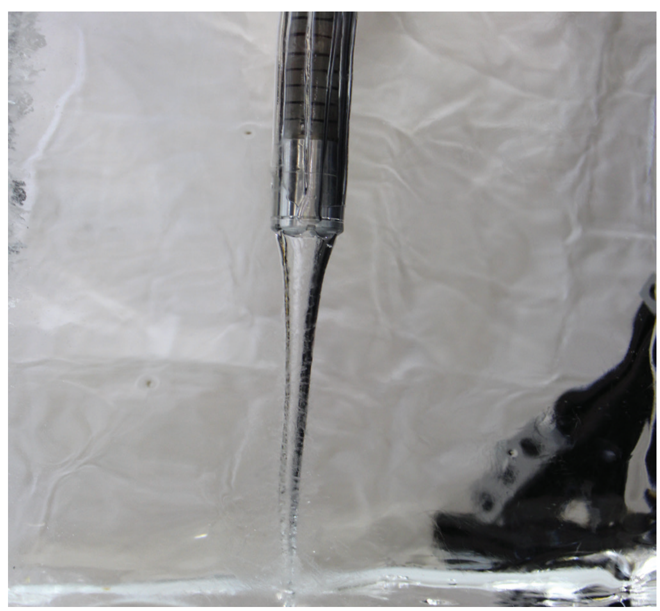
Conceptual design of ARCHIMEDES operating on Europa.

Technology Development: Europa is one of 53 confirmed moons orbiting Jupiter. While slightly smaller than Earth's moon, Europa primarily consists of silicate rock and is intriguing in that its crust consists of frozen water. Future missions under consideration to Europa would be enhanced by the ability to penetrate the multi-kilometer-thick ice crust and access the liquid water resident beneath.

To enable exploration of this fascinating celestial body, NASA SMD is funding the development and maturation of several promising ice-penetration technologies. One of these efforts is being executed just outside Austin, Texas by personnel at Stone Aerospace. Stone Aerospace is developing an entirely novel ice-penetrating technology called A Really Cool High Impact Method for Exploring Down into Europan Subsurface (ARCHIMEDES) that uses laser light carried by an optical fiber tether. ARCHIMEDES emits laser light from a nose cone and this direct laser probe allows for efficient penetration of hundreds of meters of ice. This new technology may provide future missions with access to the liquid water underneath Europa's crust.

This unique approach to ice penetration is advantageous in that it can readily be integrated with a dedicated sensor fiber, which can also accommodate instruments capable of searching for biomarkers and characterizing the radiation/light environment. The combination of the laser penetrator and integrated fiber instruments could be a powerful new tool for a future Europa lander.

The overall technical objective of the two-year ARCHIMEDES technology development effort is to design and fabricate a prototype direct-laser penetrator. The technology development project commenced on 1 March 2017 and the PI has already made significant progress towards the development goals by completing several direct laser penetrator design studies. These design studies leveraged and benefitted from a number of high-fidelity laboratory experiments. The PI has also initiated trade studies and design activities for the aforementioned fiber system.



Laboratory prototype of a direct laser penetrator making its way through ice.

Impact: This ice-penetrating technology may enable future missions to access and analyze the liquid water under Europa's crust, which will facilitate the search for life signatures within the liquid water.

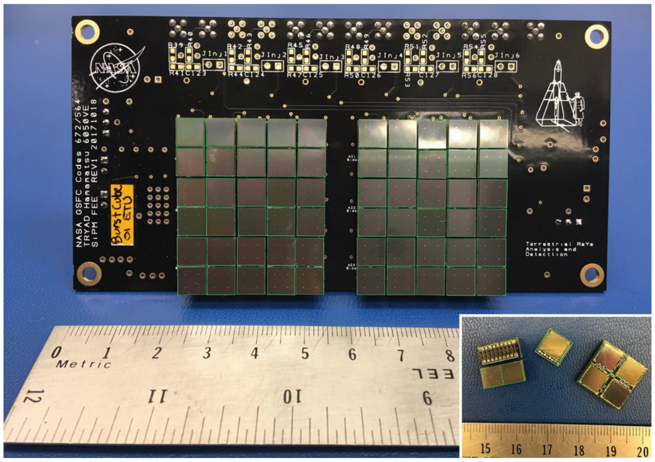
Future Plans: After prototype fabrication is complete, the prototype's performance will be assessed in harsh environmental conditions similar to those on Europa's surface. The ARCHIMEDES PI will also explore several strategies for integrating the fiber-coupled optical sensing instruments as part of the development effort.

Sponsoring Organization: SMD's Planetary Science Division is sponsoring ARCHIMEDES development through the COLDTech Program.

NEW TECHNIQUES FOR FAST NEUTRON IMAGING AND SPECTROSCOPY IN SPACE

Technology Development: A team of scientists and engineers at Goddard Space Flight Center is developing innovative technologies to expand the opportunities for neutron and gamma-ray detection from space on small satellite platforms. Traditional space-based detectors, such as the Gamma-ray Burst Monitor (GBM) on NASA's Fermi Gamma-ray Space Telescope, cannot detect events that occur in parts of the sky blocked by Earth. Employing detectors on small platforms like CubeSats will permit observations to be gathered throughout the entire sky. To fit on a CubeSat, however, these detectors must have reduced mass, volume, power, and cost.

One enabling technology includes development of large-area arrays of silicon photomultipliers (SiPM)—active detectors composed of modern scintillating materials. New scintillator materials, including both solid organic and inorganic crystals, can be grown commercially in large volumes and provide improved light output and pulse shape discrimination, which is used to distinguish neutrons from gamma rays. SiPMs consist of two-dimensional arrays of small (~50 μm) photodiode cells that are read out in parallel and provide high gain, fast output, and 20-40% detection efficiency. By tiling SiPMs together into scalable large-area arrays, the GSFC team has been able to design



Large-area arrays of 6-mm SiPMs. The insert shows the flexible carrier board design, which can accommodate various numbers of SiPMs.

highly adaptable readout devices with applications in heliospheric, planetary, and astrophysics disciplines, in addition to commercial, defense, and security applications.

The capabilities of these large-area SiPM arrays have generated great interest, particularly for CubeSat applications. In early 2018, the GSFC team will deliver flight-ready large-area SiPM arrays and front-end electronics (FEE) to the University of Alabama in Huntsville for the National Science Foundation-funded CubeSat mission, Terrestrial RaYs Analysis and Detection (TRYAD), which will measure terrestrial gamma rays associated with lightning.

Later in 2018, the team will be delivering a neutron spectrometer, the Ionospheric Neutron Content Analyzer (INCA), for a New Mexico State University (NMSU) CubeSat. Students at NMSU are building and testing the 3-unit (3U) spacecraft bus and will integrate the NASA-developed instrument in 2018. INCA employs a two-cell configuration of modern scintillators that incorporate the SiPM arrays, FEE, and a waveform-capture, application-specific integrated circuit (ASIC) to obtain excellent separation between neutrons and gamma rays.

The use of these large-area arrays has extended to an exciting new area in astrophysics with a recent CubeSat award from NASA's APRA program. The GSFC team is currently working to develop an instrument to support BurstCube, a mission specifically targeted to search for the gamma-ray counterpart to gravitational waves. The BurstCube instrument will involve four blocks of cesium-iodide crystals, operating as scintillators in different orientations within the spacecraft. When an incoming gamma ray strikes one of the crystals, it will absorb the energy and luminesce, converting that energy into optical light. Four large-area arrays of SiPMs and their associated read-out devices each sit behind the four crystals. The SiPMs will convert the light into an electrical pulse and amplify the signal. This multiplying effect makes the detector far more sensitive to faint and fleeting gamma rays.

The INCA detector, showing the two scintillators, a bias voltage board, and SiPM arrays housed in the instrument frame.

Impact: Given NASA's strategic goal to support technology miniaturization and the increased access to space provided by CubeSats and other small satellite platforms, the Agency has devoted significant effort the past several years to develop low-power, compact instrumentation that conforms to small satellite platforms. State-of-the-art packaging of SiPMs into large-area arrays functionally replaces bulky high-voltage photomultipliers. In addition, the team is also exploring advanced, custom, low-power, miniaturized ASICs to provide waveform digitization and time-of-flight measurements that make cost-effective, small satellite technologies accessible to diverse detector configurations.

Future Plans: In addition to the SiPM technology described above, the team is developing an entirely new detection technique based on a fine-grain imaging capability using multi-anode micro-channel plate photomultipliers (MCP-PMT). The fine pitch of MCP-PMT anodes, when matched to orthogonally stacked scintillator fibers, provides the ability to image neutrons by tracking the secondary protons produced by neutrons interacting within the scintillating fiber bundle.

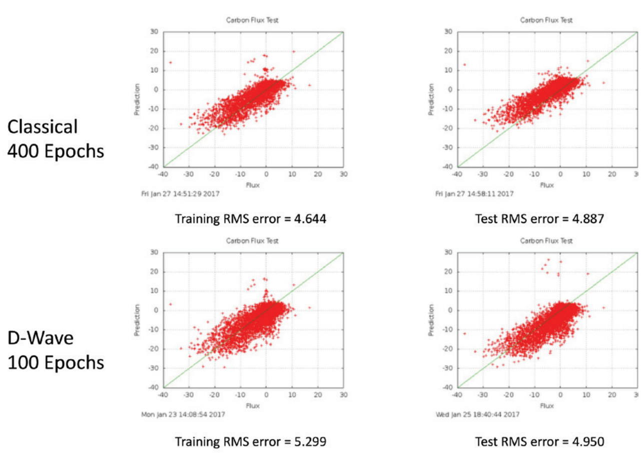
Sponsoring Organization: This work is supported by the Heliophysics Division's H-TIDeS program, the Astrophysics Division's APRA program, Goddard's Internal Research and Development program, and the National Science Foundation. Dr. G. A. de Nolfo at Goddard leads this project with engineers G. Suarez and J. DuMonthier.

ESTIMATING CARBON FLUX WITH QUANTUM COMPUTING

Technology Development: A NASA-funded team has been exploring the use of quantum annealing computers for a scientifically meaningful application—to estimate the net annual ecosystem carbon flux over land using satellite data. Carbon flux is the exchange process of carbon dioxide (CO_2) that takes place between growing or respiring vegetation and the atmosphere. This exchange process varies with season and latitude. The net global annual exchange of CO_2 plays a significant role in removing an estimated 40% of the annual emission of all sources of CO_2 into the Earth's atmosphere. Thus, scientists need to monitor and develop long-term accurate measures of this critical exchange budget to understand the Earth's climate carbon cycle.

In 2014, NASA successfully launched the Orbiting Carbon Observatory-2 (OCO-2)—the first U.S. satellite that could directly measure global-scale surface CO_2 data and Sun-induced fluorescence (a direct measure of plant greenness by a trace emission of CO_2) with 1 to 3 km resolution – high enough to glean ecosystem-scale net terrestrial sources and sinks. But calculating the net annual exchange of CO_2 flux at regional resolutions of 10 km or less also requires accurate land surface predictive models that can simulate photosynthetic and respiratory processes based on satellite-computed CO_2 flux. Undertaking this computationally challenging climate measurement is akin to picking out a face across all the crowded U.S. football stadiums on an active Sunday afternoon. What if there was a way to accurately quantify and speed up such calculations so that we could pinpoint areas of unusual or anomalous carbon flux?

An SMD-funded team led by researchers at the University of Maryland, Baltimore County (UMBC), together with researchers from Goddard Space Flight Center and scientists at Columbia University and the University of Alabama, set out to study the feasibility of employing the NASA/Google/USRA (Universities Space Research Association) D-Wave 2X quantum computer to answer that question. Located at the NASA Ames Research Center, this D-Wave system is a quantum annealing computer—a type of computer that is particularly useful for optimization, random sampling, and certain types of machine-learning applications. The team used this quantum computer to estimate carbon fluxes from three years of OCO-2 datasets to identify CO_2 sources and sinks at three sites: Utqiaġvik, Alaska; a great plain site near Oklahoma City; and a site in the Amazon rainforest. Their work has started to produce samples of calibrated monthly estimates of turbulent carbon flux inferences at the three sites, validated with CO_2 flux measurements from collocated Department of Energy instruments. As a result, this effort has also led to the development of new quantum annealing implementations of machine-learning, recurrent, neural-net algorithms for data regression applications.



Carbon flux calculated from OCO-2 data and data from atmospheric radiation monitoring stations via classical computing methods (top) and via the new quantum annealing techniques (bottom).

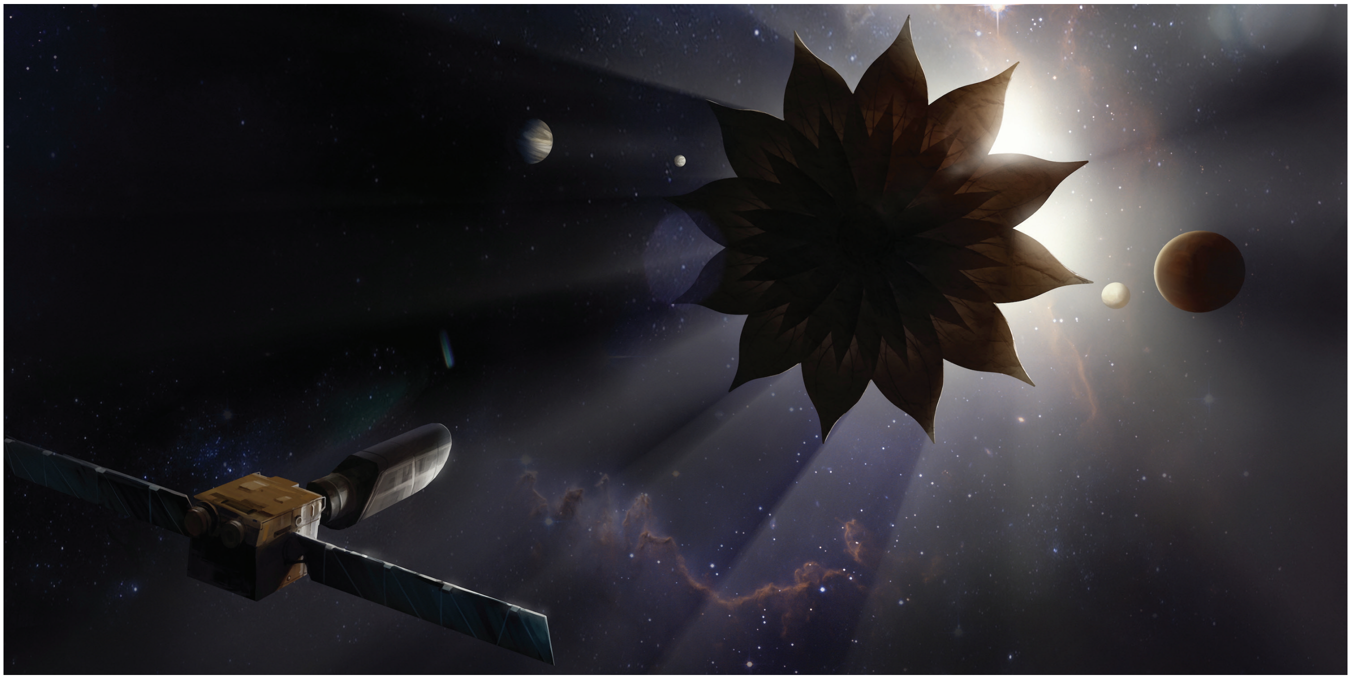
Impact: If this project is successful, it will lay the groundwork for the operational use of future quantum annealing computers (which will be much more powerful with increased numbers of quantum bits of resolution and connectivity) for analyzing flux measurements from several satellite missions across a wide variety of Earth and space science missions. As this new technique is refined to more easily and more quickly infer carbon fluxes, it will also improve analysis for a variety of other datasets, such as soil moisture flux, heat flux, ocean surface turbulent winds, etc.

Future Plans: The project has received a second funding award from SMD to continue development of quantum technology, and the team is now working to enhance algorithms and error correction techniques for dealing with the random quantum noise, a serious problem facing universal quantum computers, as this capability moves into an operational phase.

Sponsoring Organization: The Earth Science Division's AIST program provides the funding for the development of the Estimating Carbon Flux with Quantum Computing project. The Principal Investigator is Professor Milton Halem at University of Maryland Baltimore County.

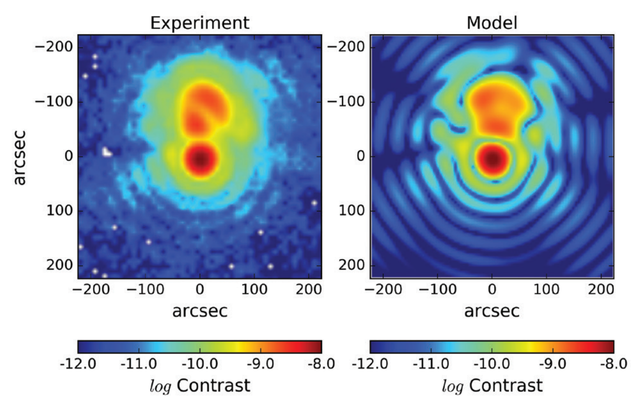
DEVELOPING STARSHADE TECHNOLOGY TO IMAGE EARTH-SIZED EXOPLANETS AROUND NEIGHBORING STARS

Technology Development: Acquiring images and spectra from planets around our neighboring stars could give us a sense of their atmospheres and habitability—but only if we can block out the star's light. The light reflected off an Earth-sized planet around a Sun-like star is about 10 billion times dimmer than the light from the parent star itself. Along with coronagraphs, a starshade is a type of occulter technology that is being developed by NASA to suppress starlight, enabling direct imaging and spectra observations to help probe for evidence of atmospheric gases, some of which may be related to life. This method requires a sufficient contrast (the ratio of the light from the planet compared to the star) of 10^{-10}, a level that cannot be reached by conventional ground-based telescopes or even current space-based telescopes operating without a starshade or a coronagraph. Unlike the coronagraph, the starshade operates outside of the telescope, on a separate space platform about 20,000 – 40,000 kilometers away, blocking the starlight before it can even enter the telescope, and allowing the faint light from exoplanets inside the habitable zone to be observed without interference.



Artist's rendition of a starshade blocking starlight from a nearby planetary system, enabling imagery of Earth-sized planets in the habitable zones around Sun-like stars. (Image Credit: Jay Wong, Los Angeles, California.)

In March of 2016, NASA's Astrophysics Division created a starshade technology development activity (now named "Starshade to TRL 5" or S5), a directed effort to mature five different starshade technologies to TRL 5 by 2022. Starshades must demonstrate three capabilities to close critical technology gaps before a starshade mission is ready to begin: starlight suppression, formation flying, and precise large deployable structures. In the starlight suppression gap there are two technologies under development: (1) validating diffraction models and error budgets through sub-scale ground tests, and (2) designing, fabricating, and testing razor-sharp optical edges that will prevent scattered sunlight from overwhelming the exoplanet light. In the formation flying gap, the lateral offset position of the starshade relative to the telescope must be determined and controlled within tens of centimeters, such that its deep shadow continuously falls on the telescope. In the precise large deployable structures gap, a 26-meter starshade must first be manufactured and deployed to within millimeters of its desired shape, and second, maintain that shape through all space environments including non-uniform heating from sunlight. Ideally, all five of these technologies should be mature enough (TRL 5) to signal readiness for infusion into a new flight project. The Wide Field Infrared Survey Telescope (WFIRST) is being made "starshade compatible" and could allow habitable exoplanet imaging using a starshade within the next decade, provided the next National Research Council Decadal Survey recommends it.



Contrast model and sub-scale experiment measurement results from the Princeton Starlight Suppression Testbed observing diffracted light around a subscale model of the starshade with known defects, producing peak contrast levels of 1.06×10^{-8} (model results show a peak contrast of 1.19×10^{-8}). (Image Credit: Anthony Harness, Princeton University).

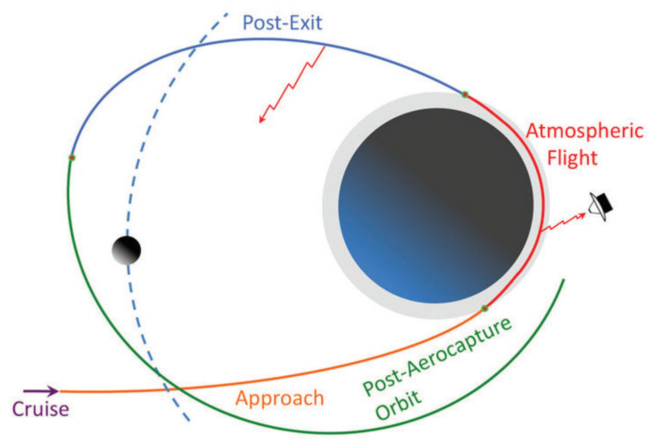
In 2017 the S5 activity focused on advancing the highest risk technology elements and completing the detailed planning to reach TRL 5 by 2022. For the starlight suppression technology, four different diffraction models from JPL, Princeton, Northrop Grumman, and the University of Colorado were shown to agree on predicted contrast within 5%. Ground-based measurements at Princeton have shown good agreement with models, reaching ≤$1x10^{-8}$ contrast, with expectations of reaching the ultimate desired performance in 2018. Measurements of scattered light from starshade edge coupons using etched amorphous metal have also shown good agreement with models and meet minimum requirements. A breakthrough in the lateral sensing of the starshade position using out-of-band light that is diffracted around the starshade has allowed the sensors expected to be used on the WFIRST coronagraph to meet requirements for formation-flying control. For the large deployable structures technologies, in 2017 S5 began a critical technical trade study comparing wrapped and folded petal architectures from JPL and Northrop Grumman. The outcome of the trade is expected in the spring of 2018 and will determine the best path forward for developing the starshade deployment and stability technologies.

Impact: The starshade and the coronagraph are the two occulter technologies NASA intends to advance to enable the first image of an Earth-like planet. Both approaches have merit and are being developed with a focus on demonstrating one or both as part of the WFIRST mission, currently scheduled to launch in the mid-2020s. The starshade would provide a higher throughput of light from the exoplanet without requiring advanced wavefront sensing technology and control optics, which enables shorter observations, but a starshade takes some extra time to move between targets compared to the onboard coronagraph. For future large space-based observatory concepts, like the Habitable Exoplanet Imaging Mission (HabEx), even larger starshades would enable deep-dive measurements of planetary spectra, atmospheric characterization, and habitability assessment by potentially working together with a coronagraph. A starshade could also be launched separately for rendezvous at a later date with any starshade-compatible telescope.

Future Plans: In the spring of 2018, S5 will submit a detailed technology development plan for all five critical starshade technologies. Pending approval from NASA, S5's goal is to reach TRL 5 on three of its five technologies—starlight suppression, edge scattering, and lateral sensing—before the upcoming Astrophysics Decadal Survey is complete. In parallel, the technologies related to deployment and shape stability will be prioritized in the ongoing trade study with sub-scale starshades planned for deployment and testing in relevant environments by 2022.

Sponsoring Organization: Starshade technology development was previously funded by NASA's Astrophysics Division via the competitive SAT program and is currently directly funded by the Exoplanet Exploration Program. Dr. John Ziemer at NASA JPL leads the starshade effort with support from Northrop Grumman Aerospace Systems. Prof. Sara Seager from MIT and Prof. Jeremy Kasdin from Princeton University are the Principal Investigators for the starshade rendezvous mission concept study.

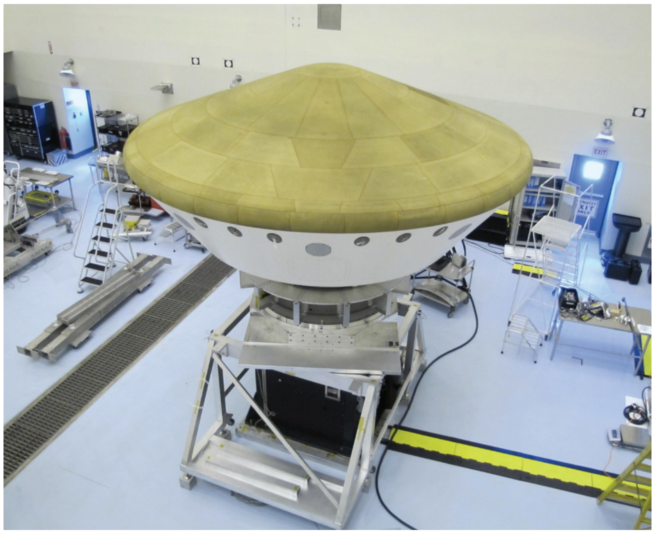
AEROCAPTURE TECHNOLOGIES ARE READY FOR FUTURE MISSION USE



The phases of a typical aerocapture maneuver sequence.

Technology Development: Aerocapture technologies have the potential to enable orbital missions to the outer planets and their satellites by the judicious use of aerodynamic forces in a planetary atmosphere. These forces can be used to guide a spacecraft from an inbound approach trajectory to its final desired orbit. During the past few decades, SMD has sponsored several technology development efforts to advance aerocapture capabilities. In 2017, SMD's Planetary Science Division commissioned the NASA Jet Propulsion Laboratory (JPL) to execute a research activity focused on assessing the readiness of aerocapture for NASA's future exploration missions. The investigation examined the state of the art for these missions with an emphasis on identifying any technology or risk reduction investments that would be most beneficial (or required) for robotic science missions.

Using aerocapture rather than a propulsive orbital insertion is beneficial for three primary reasons. First, given a particular launch vehicle, the use of aerocapture can deliver more payload mass to orbit. The reduced mission mass results in more available spacecraft resources for the science application at the final destination. Second, the use of aerocapture can reduce the time required to travel from Earth to the final exploration destination. Finally, aerocapture is associated with cost savings that result from the use of a more affordable launch vehicle.



SMD investments in aeroshell and TPS technologies contributed to the successful Mars Science Laboratory mission (whose aeroshell with the Curiosity Rover inside are shown above) and will enable future aerocapture missions. (Image Credit: NASA/JPL-Caltech)

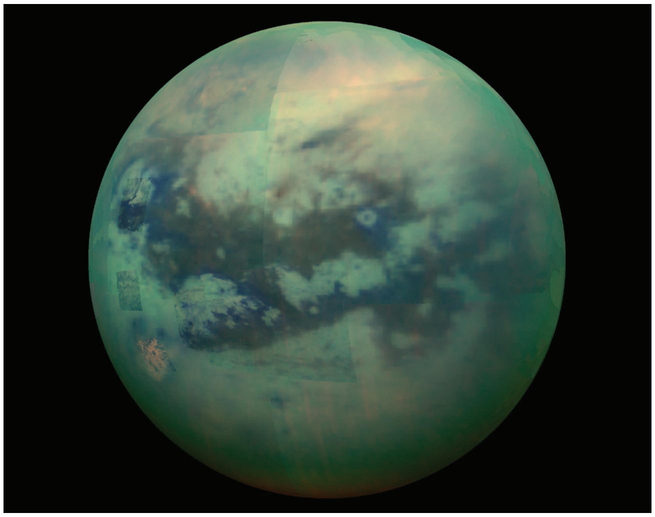
Advanced technologies necessary to implement a successful aerocapture mission include aeroshells; thermal protection systems (TPS); guidance, navigation, and control; and communications capabilities. Previous SMD technology development efforts such as the refinement of atmospheric models and the maturation of aeroshell and TPS materials have directly contributed to the current readiness of the aerocapture capability.

The JPL team conducted an extensive review of the available technologies for implementing aerocapture at multiple solar system destinations, from Venus to Neptune. The effort included a detailed examination of the timing sequence for an aerocapture maneuver and an assessment of the potential risks throughout aerocapture execution. The overwhelming conclusion from the review is that NASA is technologically ready to incorporate aerocapture for missions to Titan, Mars, and Venus. The team further concluded that there is no need to complete an aerocapture flight demonstration prior to implementing an aerocapture approach into a flight mission.

Impact: This study demonstrated that NASA's investments to mature aerocapture technologies have resulted in mission-ready capabilities that will enable and enhance future orbital missions to several important destinations in our solar system. Implementation of aerocapture techniques may reduce the cost and increase the scientific potential of these missions, which are designed to expand our understanding about the content, origin, and evolution of the solar system.

Future Plans: The study team concluded that the technology is sufficiently mature for the use of aerocapture at several planetary destinations of interest. NASA may incorporate the use of aerocapture on upcoming flagship missions as appropriate.

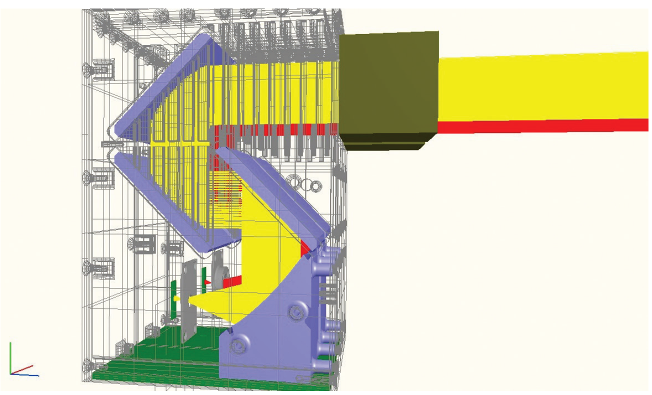
Sponsoring Organization: SMD's Planetary Science Division commissioned this technology study, which was performed by a team at NASA JPL.



Aerocapture technologies can enable orbital missions to destinations such as Saturn's moon Titan, which is shown in this image acquired by NASA's Cassini spacecraft on Nov. 13, 2015.

DEVELOPMENT OF A COMPACT MULTI-SPECTRAL PHOTOMETER FOR SPACE SCIENCE (COMPASS)

Technology Development: Earth's ionosphere is increasingly recognized as a region of space that directly impacts the development and use of space assets for modern society. For example, changing conditions in the ionosphere can adversely affect radio communications and space-based navigation systems like the Global Positioning System (GPS). Monitoring the state of the ionosphere requires space-based instrumentation and preferably a fleet of spacecraft with identical instrumentation. CubeSats provide the capability to launch many identical platforms at a reasonable total cost, but they require miniaturized science instruments to fit within the limited size, weight, and power (SWAP) constraints.

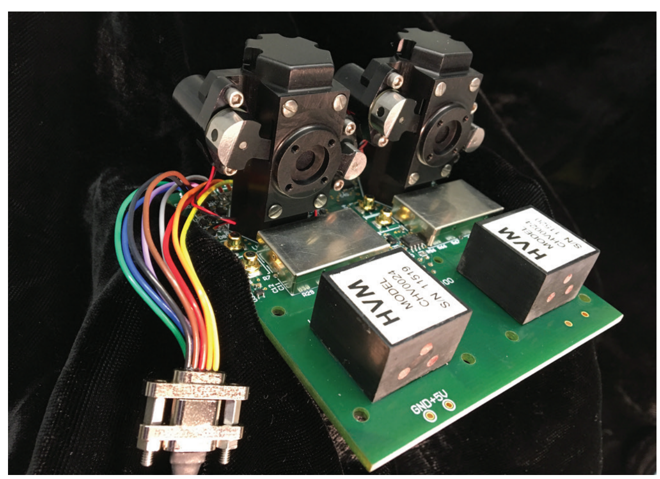


A full non-sequential ray trace was used to validate the internal baffle and optics layout prior to metal fabrication.

To address these challenges, NASA is sponsoring the Compact Multi-Spectral Photometer for Space Science (COMPASS) project to develop a low-SWAP, high-sensitivity instrument capable of monitoring the composition and variability of Earth's ionosphere and other planetary atmospheres. In collaboration with industrial partners, the team is optimizing the multilayer coating of the reflective mirrors that will enable measurements at the target far ultraviolet wavelengths (135.6 and 170 nm) and at the same time achieve good suppression at other surrounding wavelengths that would make the quantitative analysis of measurement results difficult or even impossible.

Impact: NASA Explorer-class missions like the Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics (TIMED) mission and the upcoming Ionospheric Connection Explorer (ICON) have implemented large ionosphere-targeting vacuum ultraviolet (VUV) spectrographs. These large and costly spectrographs have provided and continue to provide pioneering measurements of ionospheric variability in response to solar influences. The COMPASS development addresses the recommendation in the National Academies' Decadal Survey for "small space missions" to diversify space physics research by enabling VUV research on CubeSat-scale vehicles.

COMPASS is a narrowband VUV photometer with 20 times the sensitivity of larger multi-pixel spectrographs and will complement Explorer mission VUV sensing through contemporaneous coverage of key atomic oxygen (130.4 and 135.6-nm) and molecular nitrogen Lyman-Birge-Hopfield (LBH) band emission features. A low-resource, flight-ready VUV photometer, COMPASS enables global, multi-point, and trans-hemispheric constellation missions and is capable of supporting dayside, auroral zone, and nightside measurements at modest spatial resolution. COMPASS narrowband photometry will also enable the low-bandwidth, CubeSat-based, atmospheric sensing envisioned for interplanetary missions targeting hydrogen, oxygen, and nitrogen emissions throughout our solar system.



Dual VUV photomultiplier tubes with independent power supplies are located behind the folded optics on a single electronics board that communicates with the CubeSat flight computer.

Future Plans: During the last half year of the project, the COMPASS team plans to assemble one complete prototype of the instrument. This prototype will undergo the extensive environmental testing, photometric responsivity tests, and VUV spectral characterization necessary to demonstrate ascension to TRL 5, after which the instrument will be ready for entry-level flight development to support a broad range of Heliophysics and Planetary Sciences CubeSat missions.

Sponsoring Organization: COMPASS is supported by the Heliophysics Division via the H-TIDeS program. Dr. Harald Frey from the Space Sciences Laboratory at the University of California Berkeley is the PI. He is supported by instrument mechanical/electronic co-Investigator Dr. Rick Doe (SRI International) and optic co-Investigator Dr. John Noto (Computational Physics, Inc.).

WIRELESS NETWORKS GATHER SOIL MOISTURE DATA IN THE ARCTIC

Technology Development: Accurate measurement of soil moisture is important to numerous fields including agriculture, weather prediction, and the study of climate change. An SMD-sponsored project—the Soil moisture Sensing Controller And oPtimal Estimator (SoilSCAPE)—is helping scientists monitor soil moisture at several sites in the continental U.S. and Alaska. SoilSCAPE sensor webs are autonomous, wireless networks that provide near-real-time data on soil moisture profiles. Recently, SoilSCAPE teamed with NASA's Arctic Boreal Vulnerability Experiment (ABoVE)—a far-reaching, 10-year, NASA-led field campaign that kicked off in 2016—to study environmental changes and ecosystem vulnerability in the Arctic. The SoilSCAPE team successfully installed and tested two networks of in situ soil temperature and moisture sensor webs in Alaska that are providing measurements to support ABoVE.

A SoilSCAPE base station (coordinator) at an Alaska site. The coordinator receives data from the SoilSCAPE probes (the wireless sensor network, or WSN) and sends it to the lab via satellite. The coordinator also receives commands from the lab and relays them to the SoilSCAPE sensors using the same communication path in reverse.

SoilSCAPE networks were initially developed to validate data from airborne and spaceborne missions such as NASA's Soil Moisture Active Passive (SMAP) mission. Previous SoilSCAPE deployment locations included sites in California, Arizona, Michigan, and Oklahoma. The California and Arizona sites are still collecting and providing data in real time. To support operations in the harsh Arctic environment, the SoilSCAPE team had to enhance the network's hardware. In addition, SoilSCAPE communication interfaces were redesigned to enable energy-efficient transmission of the data from the remote region via Iridium satellite links.

Beginning in August 2016, the SoilSCAPE team placed several sensor nodes within the permafrost active layer at two Alaska sites—Happy Valley and Prudhoe Meadow. Each node contains soil probes at four depths, ranging from 5 cm below the tundra surface to near the permafrost table. Data from the probes are gathered at each node and wirelessly transmitted to a locally placed base station (coordinator). The coordinator re-transmits the data via cellular or satellite connections to the laboratory, where it is decompressed and made available to users via an online database. The team can also send signals to the coordinator, asking it to task the nodes on demand.

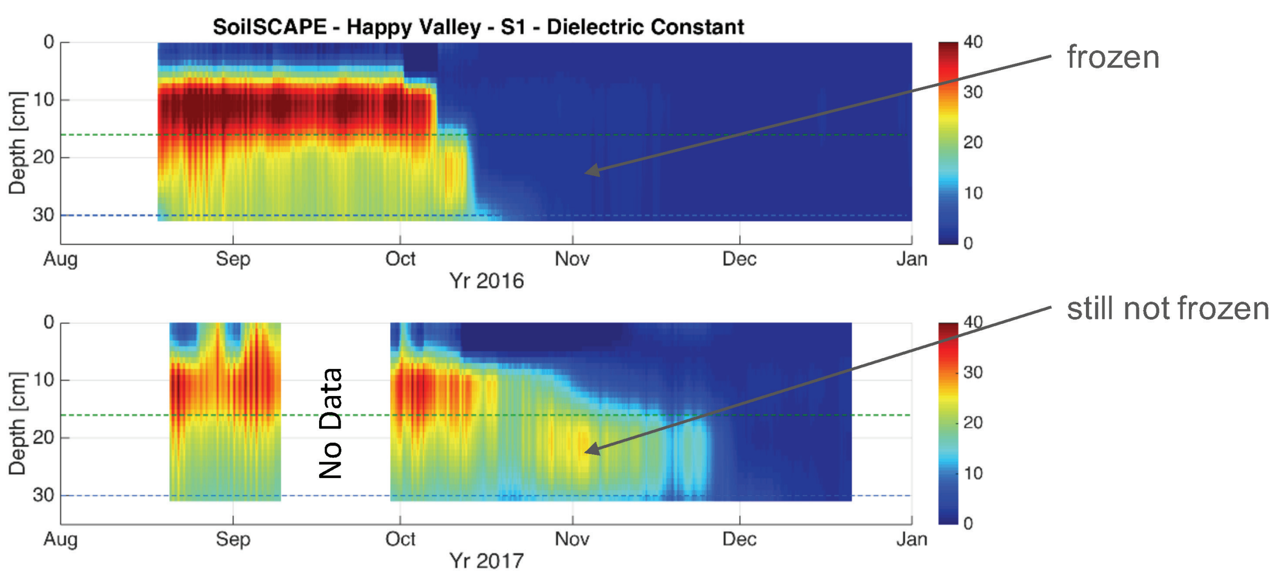
Following several months of testing, the two arctic SoilSCAPE sites supported the ABoVE campaign's scientific research flights from April through October 2017, providing in situ soil moisture and temperature data to complement the airborne measurements and to provide validation data for airborne data products. In addition, data from these SoilSCAPE sites have provided scientists with new insights about the timing and the profile characteristics of freeze-thaw transitions that occur in the permafrost active layer. The network continues to collect and transmit data, even during the winter months.

More information on SoilSCAPE, including access to SoilSCAPE data, is available online at: [http://soilscape.usc.edu.](http://soilscape.usc.edu)

Impact: Measuring soil moisture and temperature profiles in the permafrost soils of the Arctic is especially crucial to support climate change research because these regions are experiencing the effects of climate change faster than anywhere else on Earth. By supporting the ABoVE project, SoilSCAPE is enabling critical research to understand and predict arctic ecosystem change and vulnerability. The results of these studies have significant societal impacts; they allow scientists to understand the feedback from climate warming and permafrost thaw trends and to characterize and predict damage to infrastructure in arctic communities.

Future Plans: The SoilSCAPE team expects the two Alaska sites to operate unattended for 1-2 more years, continuing to gather valuable soil moisture and temperature data on the permafrost active layer in this remote, but important, region. Multi-year, high-temporal-resolution data from such networks, in synergy with temporally sparse but spatially diverse airborne and spaceborne remote sensing products, will also enable scaling up of in-situ observations to regional domains.

Sponsoring Organization: The Earth Science Division's AIST program provided the funding for the development of the SoilSCAPE project. The Principal Investigator is Mahta Moghaddam at the University of Southern California.



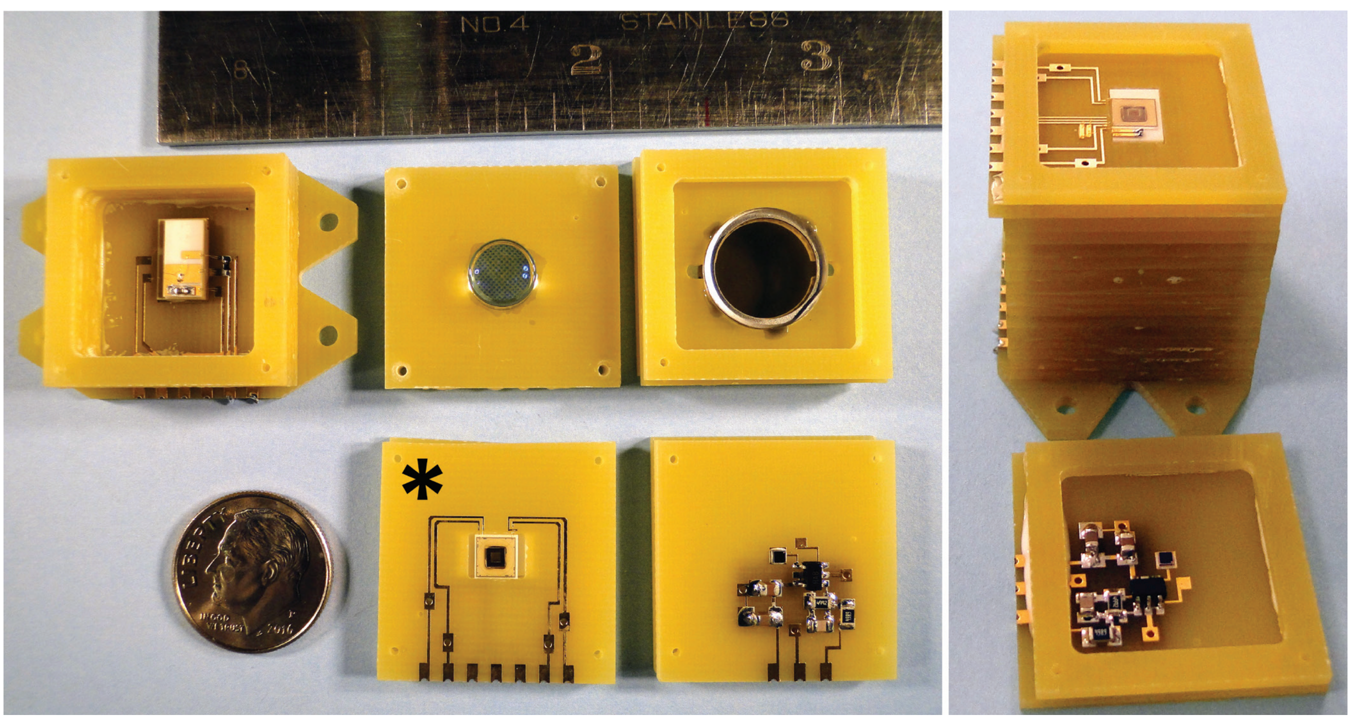
SoilSCAPE measurements of the dielectric constant at the Happy Valley site in Alaska show that Fall 2017 was observed to be much warmer than Fall 2016, and that the transition to a frozen state throughout the active layer profile took place quite a bit later.

MINIATURE MAGNETOMETER WILL ENABLE SPACE EXPLORATION ON RESOURCE-CONSTRAINED PLATFORMS

Technology Development: NASA is sponsoring a joint effort by researchers at the Johns Hopkins Applied Physics Laboratory (APL) and the National Institute of Standards and Technology (NIST) to develop a novel miniature absolute scalar magnetometer based on a micro-fabricated alkali-metal vapor cell. The vapor cell has a volume of only 1 mm^3 so that it can be efficiently heated to its operations temperature by a specially designed resistive heater implemented in multiple layers of a transparent semiconductor chip. The small volume and mass and the minimal power requirements of this magnetometer will enable it to serve as an ultra-precise inflight calibration standard for resource-constrained future spaceflight missions. The instrument will be qualified for operation in a space environment during flight on a sounding rocket funded by NASA for an international scientific campaign to explore the auroral cusp region.

In 2017, the team fabricated prototypes of the power supply and the control electronics. These components underwent extensive testing to verify operation in the targeted environment. For this purpose, a simulator for the variable and rotating magnetic field observed in the reference frame of the rocket was constructed. During testing, the team identified several problems with the prototype that will be resolved during the development of the flight instrument.

Impact: The magnetic field is a fundamental physical quantity, and its precise measurement plays a central role in addressing the scientific objectives of many planetary, solar, and interplanetary science missions. Deployment of instruments on such missions is subject not only to need, but also to resource accommodation. The absolute scalar magnetometer under development yields a quantum reduction of resource needs compared with its peers. A prototype built has a total mass of fewer than 500 g and uses less than 1 W of power, while maintaining a sensitivity comparable to present state-of-the-art absolute magnetometers. Spacecraft should be able to accommodate this instrument even under severe resource constraints, so widespread use of such instruments in future missions is anticipated.



Magnetometer sensor components (left) and stacked sensor assembly (right). The micro-fabricated alkali-metal vapor cell is located in the center of the component marked with an asterisk.

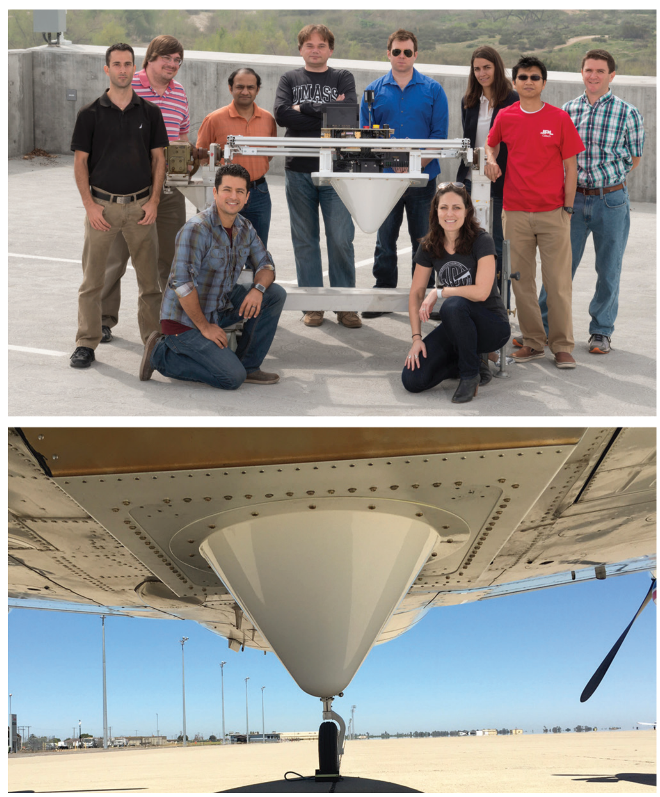
Future Plans: Following completion of the magnetometer, the team will integrate the flight experiment with one of two sounding rockets of the Twin Rockets to Investigate Cusp Electrodynamics II (TRICE-2) mission at the NASA Wallops Flight Facility. Both sounding rockets will then be shipped to Andøya, Norway, where they are scheduled for launch in December 2018. The flight demonstration will qualify the instrument for use in future scientific missions in the space environment of Earth and other planets. Most scientific applications require measurements of the magnetic field direction in addition to the magnitude. The upgrade to a vector instrument is therefore the next planned step in this instrument development effort.

Sponsoring Organization: The development of the sounding rocket experiment is sponsored by the Heliophysics Division via the H-TIDeS program. Development of other aspects of the technology are sponsored by the Planetary Science Division via the PICASSO and MatISSE programs. The Principal Investigator is Dr. Haje Korth at the Johns Hopkins Applied Physics Laboratory.

DOPPLERSCATT'S SIMULTANEOUS OCEAN WIND AND CURRENT MEASUREMENTS EMPLOYED IN TWO STUDIES

Technology Development: A NASA-developed airborne instrument called DopplerScatt participated in two large-scale oceanographic experiments in April and May of 2017. A Ka-band Doppler scatterometer, DopplerScatt's ability to take simultaneous measurements of ocean surface winds and water currents is a new science capability—one that could improve our understanding of air-sea interactions and their influence on Earth's climate. Ocean surface currents impact heat transport, surface momentum and gas fluxes, ocean productivity, and marine biological communities. Ocean currents can even have societal impact since they can affect shipping and disaster management. Ocean vector winds are a key variable governing the transfer of momentum, gases, and latent heat between the atmosphere and the ocean. The ability to simultaneously measure ocean winds and currents improves the accuracy of both individual measurements, as there is an intrinsic two-way coupling between them.

In April 2017, DopplerScatt participated in the Submesoscale Processes and Lagrangian Analysis on the Shelf (SPLASH) campaign led by the Consortium for Advanced Research on Transport of Hydrocarbon in the Environment (CARTHE). The goal of SPLASH was to investigate the movement of potential oil spills and leaks in the Gulf of Mexico. For SPLASH, the DopplerScatt team installed the instrument on a King Air B200 aircraft and flew it over the coastal shelf of the U.S. Gulf Coast. DopplerScatt's measurements complemented in situ data gathered by hundreds of drifting floats and shipborne instruments as well as high-resolution model outputs from the U.S. Naval Research Laboratory. The CARTHE team used DopplerScatt to decide where to place the drifters, and the models and in situ instruments were, in turn, used to further validate DopplerScatt measurements.



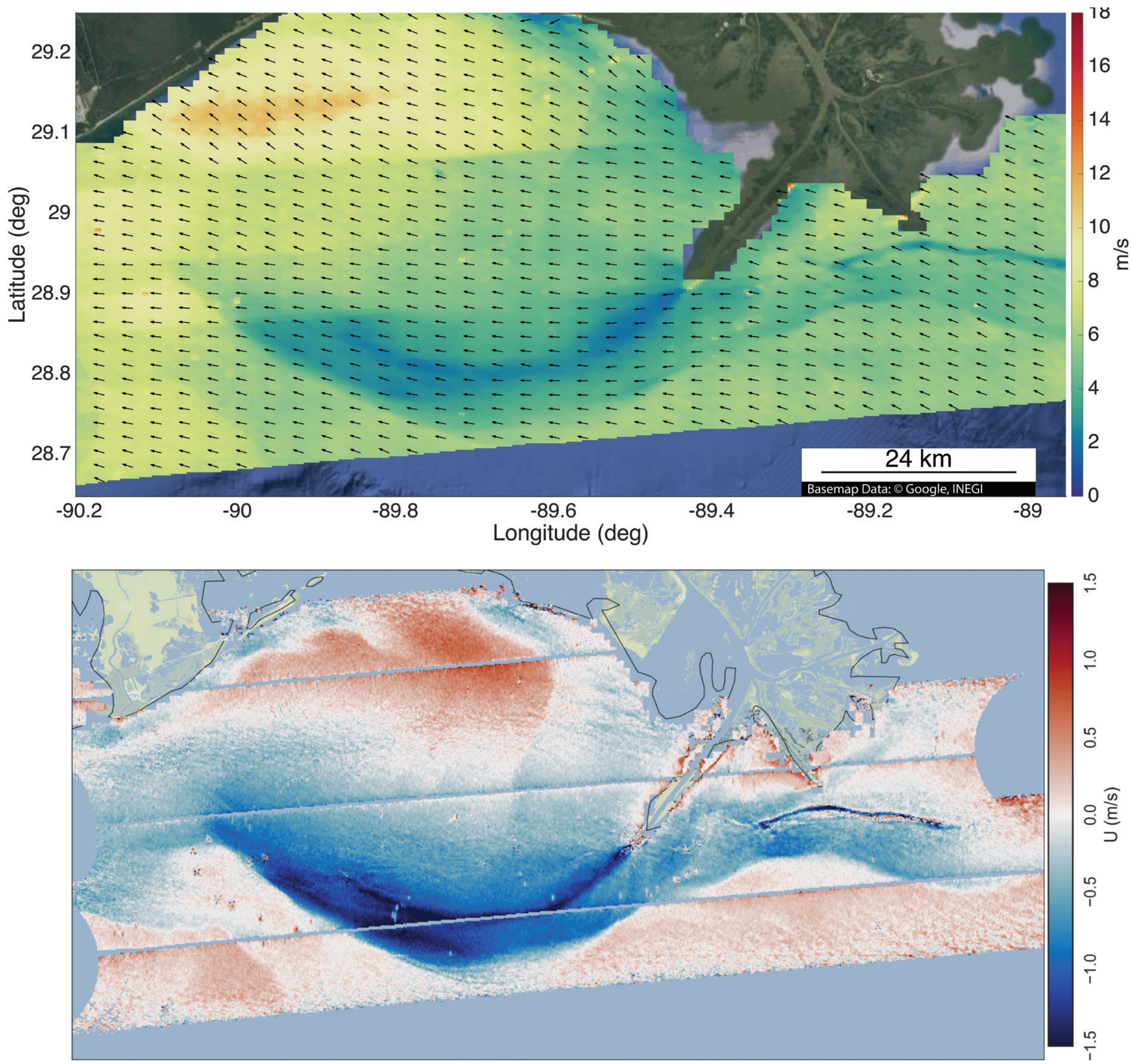
Top: The DopplerScatt team with the radar at JPL before aircraft installation. Bottom: DopplerScatt aboard King Air B200. (Image credit: NASA/JPL-Caltech)

In May 2017, DopplerScatt participated in the Keck Institute for Space Studies (KISS) Controlled, Agile, and Novel Ocean Network (CANON) campaign, which is designed to optimize robotic sampling capabilities to resolve evolving small-scale ocean instabilities. For the KISS campaign, a team from Caltech/JPL, the Monterey Bay Aquarium Research Institute, and Remote Sensing Solutions collected in situ data in Monterey Bay using different autonomous underwater vehicles and gliders. DopplerScatt provided data to investigate the relationship between the observed Doppler velocities measured by the instrument and currents at various depths.

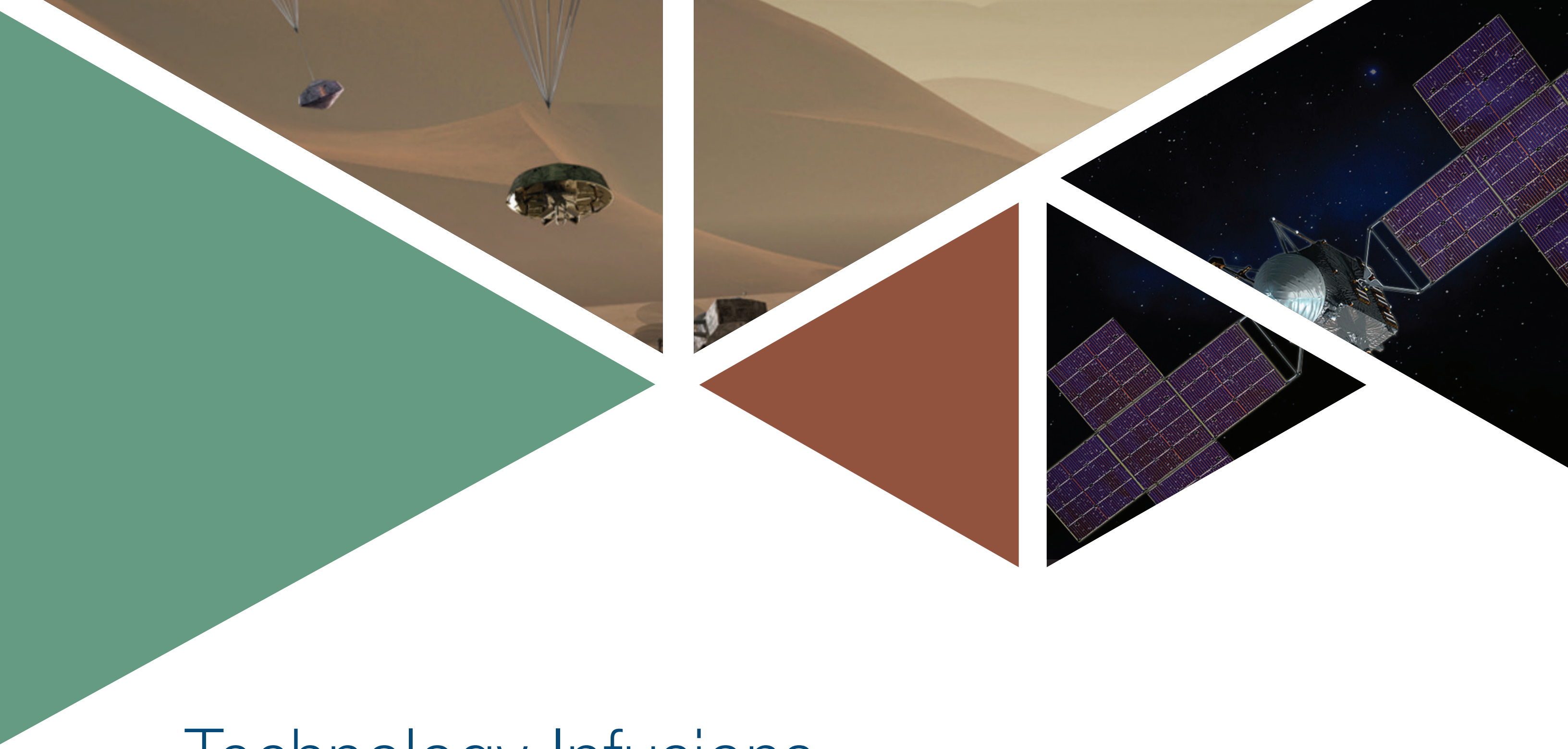
Impact: While DopplerScatt can be used on future NASA airborne science missions, the technology development also lays the groundwork for an eventual spaceborne instrument, which would enable global measurements of ocean surface winds and water currents simultaneously for the first time.

Future Plans: DopplerScatt is currently funded under NASA's Airborne Instrument Transition Technology (AITT) Program with the goal of transitioning it to a NASA airborne platform and making it campaign-ready. DopplerScatt is scheduled to collect data along the California coast in spring/summer of 2018.

Sponsoring Organization: The Earth Science Division's IIP program provided the funding for DopplerScatt development. The Principal Investigator is Dr. Dragana Perkovic-Martin of NASA JPL.



Top: Wind speed and direction in the Gulf of Mexico for April 18, 2017, as measured by DopplerScatt during the SPLASH campaign. Bottom: DopplerScatt-measured U component (East-West) of surface current for the same data collection. (Image credit: NASA/JPL-Caltech)



Technology Infusions

GEMINI PLUS ENABLES NEXT-GENERATION PLANETARY COMPOSITION MEASUREMENTS

Technology Infusion: NASA has funded the development of a new high-purity germanium gamma-ray detector—the GeMini Plus—for use in upcoming planetary exploration missions. High-purity germanium detectors provide superior performance compared to other gamma-ray detectors. This development is being carried out jointly by Johns Hopkins University Applied Physics Laboratory (JHU/APL) and Lawrence Livermore National Laboratory (LLNL).

Planetary gamma-ray spectroscopy provides measurements of the chemical makeup of the surfaces of planets, moons, and asteroids. This information provides chemical maps that allow scientists to understand how these objects formed and changed over time.

In 2017, the GeMini Plus team wrapped up its three project objectives:

1. Designing and testing a new low-resource germanium gamma-ray detector that is robust enough to withstand the vibrational rigors of rocket launch and environmental extremes of spaceflight

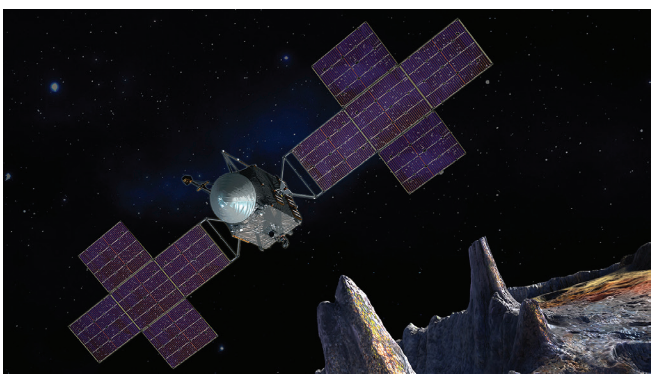
2. Developing and testing new flight-ready electronics that provide superior performance compared to currently designed electronics

The GeMini Plus gamma-ray detector contains a high-purity germanium sensor enclosed by a temperature sealed housing (gold cylinder). The sensor is cooled to liquid nitrogen temperatures by a long-life cryocooler (silver cylinders) (Image credit: LLNL).

3. Demonstrating the capability to fully eliminate sensor damage from high-energy cosmic radiation

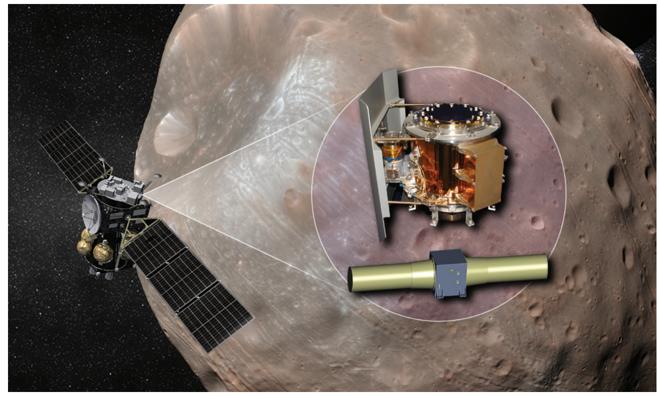
Impact: The work carried out on this program has led to the selection of gamma-ray detectors employing GeMini Plus technology for two future planetary missions and one planetary concept development mission under study.

Psyche: A NASA Discovery mission, Psyche is scheduled to launch in 2022 and will arrive at the main belt asteroid (also named Psyche) in 2026. Gamma-ray measurements provided by the Psyche mission will quantify the amount of nickel and other elements the asteroid contains. These measurements will help determine if the Psyche asteroid is an exposed planetary core, or if it formed by some other exotic process.



NASA's Psyche mission carries a gamma-ray detector to measure the elemental composition of the asteroid 16 Psyche (Image credit: NASA/Arizona State University).

MMX: The NASA-funded Mars-moon Exploration with Gamma rays and Neutrons (MEGANE) investigation was selected via NASA's 3rd Stand Alone Mission of Opportunity Notice (SALMON-3) Announcement of Opportunity to fly on the Martian Moons eXploration (MMX) mission being developed by the Japan Aerospace Exploration Agency (JAXA). MMX will visit the two moons of Mars—Phobos and Deimos. MEGANE will employ GeMini Plus technology in a gamma-ray spectrometer designed to provide answers to fundamental questions about the formation of Mars' moon Phobos.



The NASA-funded MEGANE investigation on Japan's MMX mission will measure the elemental composition of Mars' moon Phobos (Image credit: JHU/APL, JAXA)

Dragonfly: NASA selected Dragonfly—a robotic concept development mission to Saturn's moon, Titan—under Step 1 of the Agency's New Frontiers Program. If selected under Step 2, Dragonfly will launch in the mid-2020s and will fly a rotorcraft across Titan's surface. Dragonfly will carry a gamma-ray detector to measure the elemental composition of Titan's surface at multiple locations.

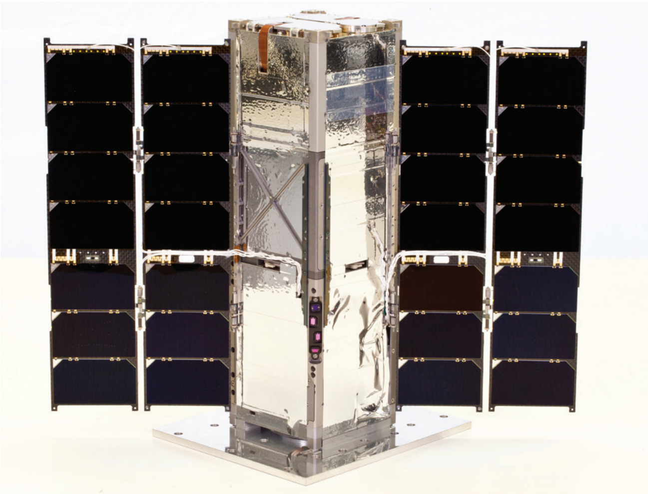
Artist's depiction of the Dragonfly mission (Image credit: JHU/APL and Steve Gribben).

Future Plans: The GeMini Plus team plans to continue to characterize the detectors for radiation damage and recovery using a high-temperature annealing process.

Sponsoring Organization: The The Planetary Science Division's Maturation of Instruments for Solar System Exploration (MatISSE) program provides funding for this effort to a team led by PI David J. Lawrence of the Johns Hopkins University Applied Physics Laboratory; the program is being jointly carried out by JHU/APL and LLNL.

RAVAN CUBESAT SUCCESSFULLY DEMONSTRATES TWO RADIATION MEASUREMENT TECHNOLOGIES

Technology Infusion: The Radiometer Assessment using Vertically Aligned Nanotubes (RAVAN) CubeSat has met its goal of validating two new technologies to measure Earth's radiation imbalance—the difference between the amount of energy from the Sun that reaches Earth and the amount that is reflected and emitted back into space. Launched in November 2016, the 3U CubeSat began taking Earth radiation data on January 25, 2017, and by August 9, the project team had met all mission objectives and declared the demonstration of the new technologies a success.



The RAVAN CubeSat successfully demonstrated new technologies to measure Earth's radiation imbalance and predict future climate change (Image credit: JHU APL/Blue Canyon Technologies)

RAVAN employs two technologies that had never before been used on an orbiting spacecraft: carbon nanotubes that absorb outbound radiation and a gallium phase change blackbody for calibration. Among the blackest known materials, carbon nanotubes absorb virtually all energy across the electromagnetic spectrum. Their absorptive property makes them well suited for accurately measuring the amount of energy reflected and emitted from Earth. Gallium is a metal that melts—or changes phase—around body temperature, making it a consistent reference point. RAVAN's radiometers measure the amount of energy absorbed by the carbon nanotubes, and the gallium phase change cells monitor the stability of the radiometers.

Interestingly, the solar eclipse on August 21, 2017 gave researchers a unique opportunity to further test an important carbon nanotube attribute: the strong sensitivity to rapidly changing energy outputs. While designed to measure the amount of reflected solar and thermal energy emitted from Earth into space, during the eclipse RAVAN's highly sensitive nanotubes were trained instead on the Sun to detect changes in the amount of incoming solar energy. Because the researchers knew the CubeSat's location and the percentage of eclipse it would measure, it was easy for the team to compare the satellite's data to the known solar irradiance. As the moon passed between Earth and the Sun, RAVAN's instruments responded rapidly and accurately to measure the diminishing solar energy that was visible to the satellite's detectors.

The RAVAN flight payload with covers open, showing the four radiometer sensors. (Image credit: JHU APL/L-1 Standards and Technology)

RAVAN is currently trained back at Earth and operating well beyond its original six-month mission time frame. The project team continues to monitor the satellite's instrument performance, perform data analysis, and compare its measurements with existing model simulations of Earth's outgoing radiation.

Impact: While the RAVAN technology demonstration comprises a single CubeSat, in practice, a future mission could operate many such CubeSats in a constellation. Currently, instruments for measuring Earth's outgoing energy are housed aboard a few large satellites, and while they have a high spatial resolution, they cannot observe the entire planet simultaneously the way a constellation of CubeSats could. Global measurements of Earth's radiation would help researchers gain a better understanding of the planet's changing climate.

Future Plans: RAVAN will continue to operate in 2018, assessing the long-term stability of the radiometer sensors and collecting a larger data set of Earth's outgoing radiation.

Sponsoring Organization: The Earth Science Division's InVEST program provided the funding for the RAVAN mission. The Principal Investigator is William Swartz at Johns Hopkins Applied Physics Lab.

COLLOID MICROTHRUSTERS DEMONSTRATED ON LISA PATHFINDER

Technology Infusion: A colloid microthruster provides electric micropropulsion for drag-free and fine pointing applications. It uses an electrospray (electrostatically generated and accelerated charged droplets) to provide spacecraft control at tens of micronewtons of thrust (about the weight of a mosquito!) with better than 100 nanonewton precision, mainly to push back against solar photon pressure.

A team of engineers at Busek Co., Inc. and NASA JPL developed eight colloid micro-newton thrusters under NASA's Space Technology 7 Disturbance Reduction System (ST7-DRS) project. These microthrusters proved their remarkable capabilities in a demonstration onboard the European Space Agency's (ESA) Laser Interferometer Space Antenna (LISA) Pathfinder mission, where they controlled the spacecraft's position to within 10 nm/√Hz (about the width of a DNA helix). Interferometric measurement of free-floating test masses within the spacecraft showed that the microthruster technology met all requirements, providing the first-of-its kind demonstration of an electrospray thruster operating in space. The thrusters performed for over 90 days during the nominal and extended mission with all operations ending successfully in July 2017.

Busek colloid microthrusters on the LISA Pathfinder spacecraft just prior to thermal blanket installation and launch. (Image Credit: ESA/Airbus.)

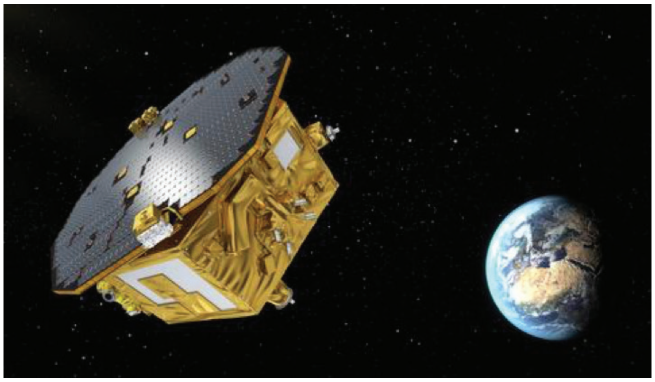
Launched in December 2015, LISA Pathfinder demonstrated most of the key technologies necessary for detecting and measuring gravitational waves, including both cold gas (an ESA-led technology) and colloid microthrusters. Both of these micropropulsion technologies are being considered for infusion into the full ESA-led LISA mission, which is currently in Phase A with launch scheduled for 2034. The cold gas microthrusters are currently considered as the baseline and the colloid microthrusters are a potential U.S. contribution. In 2017, NASA started funding development of a fully redundant and long-life version of the colloid microthrusters, with the goal of being flight-ready by 2022 when a final decision will be made on the U.S. contribution to ESA's LISA mission.

NASA also plans to employ microthruster technology as a replacement for the reaction wheels in the HabEx

Decadal Study mission concept. In this application, colloid microthrusters would provide more precise pointing of the observatory without causing mechanical jitter or the need for heavy vibration isolation structural elements, enabling future exoplanet imaging missions that use coronagraphs.

Impact: Colloid microthrusters enable two exciting new areas of astronomy and astrophysics research: space-based detection and measurement of gravitational waves and exoplanet imaging using coronagraphs.

Detecting gravitational waves in space requires operating three spacecraft "drag-free" in an equilateral triangle formation separated by 2.5 million kilometers. Elimination of all disturbances on the spacecraft is necessary to achieve the picometer-level interferometric measurements of the strain between free floating test masses on each spacecraft. As with LISA Pathfinder, the largest disturbance on each spacecraft comes from solar photon pressure, about 7 micronewtons per meter squared of solar array area. Space-based measurements of gravitational waves will enable new understanding of binary star and black hole mergers going back to when galaxies first started forming after the big bang.



Artist's concept of ESA's LISA Pathfinder spacecraft, which carried the NASA-developed microthrusters on a mission to demonstrate key technologies needed to detect gravitational waves in space. (Image Credit: ESA)

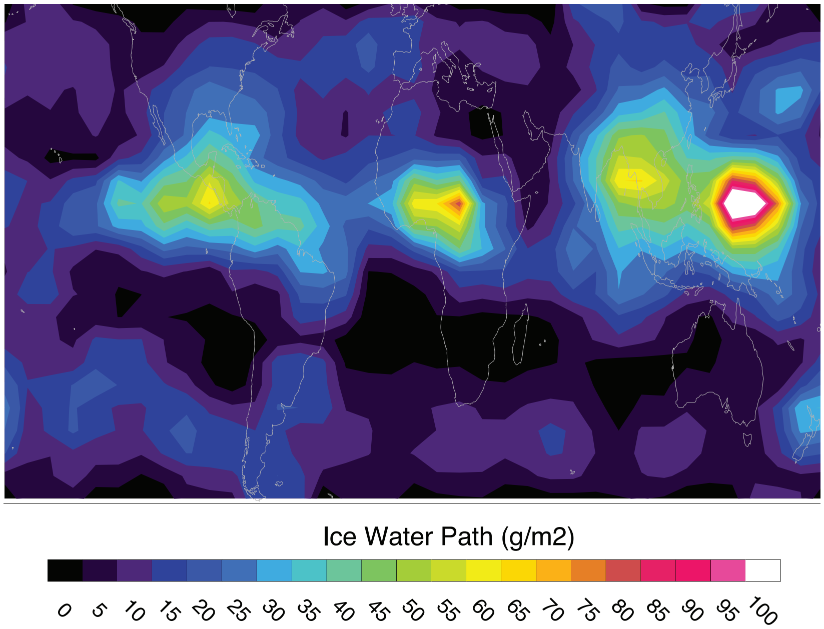
Space-based exoplanet imaging and spectroscopy will provide the first look at another Earth-like planet around a Sun-like star. To block out the light from the parent star, coronagraph technology is being developed for the WFIRST Mission and HabEx Decadal Study Mission Concept. Providing adequate suppression of the starlight requires a mechanically ultra-stable platform and precision pointing. Colloid microthrusters can perform this function while using less overall mass than the conventional reaction wheel and vibration isolation hardware schemes commonly used in space-based astronomical observatories.

Future Plans: For any future application, the reliability and lifetime of the colloid microthrusters must be demonstrated on the ground for at least four years of continuous operation. Unlike other propulsion devices, colloid microthrusters must operate continuously during science measurements to push back against solar photon pressure. Physics-based lifetime models have been developed and, along with lessons learned from LISA Pathfinder, are informing the fully redundant design and validation activities going on now during ESA's LISA Project Phase A. NASA's new microthruster design will be ready for review in two years, with environmental, performance, and lifetime validation planned for 2022, when NASA is expected to make a formal decision about its contribution to LISA.

Sponsoring Organization: NASA's Astrophysics Division is directly funding the development of colloid microthruster technology through the Physics of the Cosmos Program. In the past five years, NASA has also funded this technology through other competitive SAT and Small Business Innovation Research (SBIR) awards. Dr. Vlad Hruby was the PI for the colloid microthruster technology at Busek Co., Inc. for ST7-DRS. Dr. John Ziemer was the Payload Systems Engineering for ST7-DRS and is currently the PI leading the technology development work for LISA at NASA JPL.

ICECUBE DEMONSTRATES NEW CAPABILITY TO MEASURE CLOUD ICE FROM SPACE

Technology Infusion: IceCube—a tiny, bread loaf-sized satellite—has produced the world's first map of the global distribution of atmospheric ice in the 883-Gigahertz (GHz) band. Information about cloud ice enables researchers to better understand Earth's weather and changing climate. Sensing atmospheric cloud ice requires that scientists deploy instruments tuned to a broad range of frequency bands. However, it is particularly important to fly submillimeter sensors



This global map of mean cloud ice was generated using data from IceCube in 2017.

like the one on IceCube because this wavelength fills a significant data gap in the middle and upper troposphere where ice clouds are often too opaque for infrared and visible sensors to penetrate. Measurements in these wavelengths also reveal data about the tiniest ice particles that cannot be detected clearly in other microwave bands.

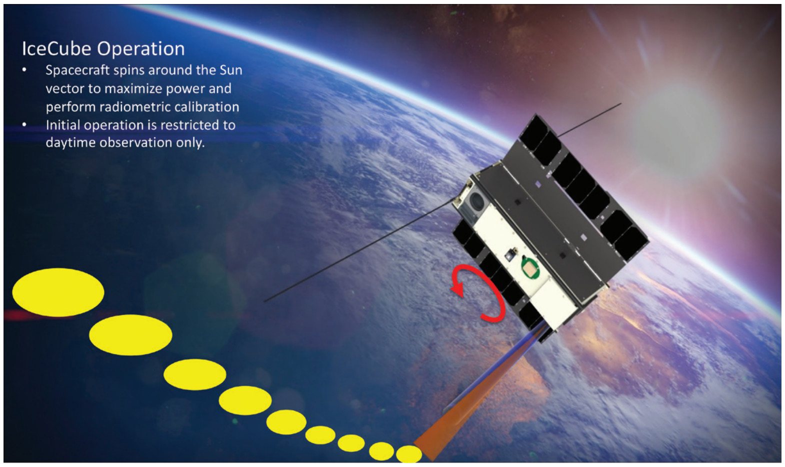
Previously, instruments observing at submillimeter wavelengths had only been flown aboard high-altitude aircraft, which limited data gathering capabilities. To demonstrate how new technologies could help fill this observation gap, SMD funded the IceCube project, with access to space enabled by NASA's CubeSat Launch Initiative. Built in-house at GSFC by a team led by Dong Wu, IceCube is flying an 883-GHz radiometer developed by Virginia Diodes Inc. on a 3U CubeSat platform to test and validate a low-cost commercially available radiometer in the space environment. From its vantage point in space, IceCube is capable of providing global cloud ice data in the important submillimeter wavelength.

Deployed from the International Space Station on May 16, 2017, IceCube began operations in June and is currently demonstrating the utility of submillimeter wave radiometry measurements to advance our understanding of cloud ice and its role in climate change.

Impact: Not only was the demonstration of the new capability to collect submillimeter cloud ice observations from space a success, the IceCube team gained important insights into how to efficiently develop a CubeSat mission with limited funds on a short schedule.

Future Plans: This type of low-cost receiver technology will prove useful for future missions designed to gather important measurements such as the targeted cloud, convection, and precipitation observables recommended by the 2017 National Research Council Decadal Survey (DS). The DS program element is aimed at investigating the coupled cloud-precipitation state and dynamics for monitoring the global hydrological cycle, and understanding contributing processes including cloud feedback, in which multi-frequency passive microwave and sub-mm radiometry are identified as candidate measurement approaches.

Sponsoring Organization: SMD's CubeSat Initiative and the Earth Science Division's InVEST program provided the funding for the IceCube mission. The Principal Investigator is Dong Wu at NASA GSFC.



Operation of the IceCube satellite.

Appendix A: The SMD Technology Development Strategy

Sustained investment in technology development and infusion of viable new technologies are 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.[3] SMD's approach is to mature enabling technologies years in advance of mission implementation, thereby retiring risk, reducing cost, and increasing the likelihood that new technologies will be incorporated into flight projects.

SMD aligns its technology investment strategy with the Agency's overarching approach, which is described in detail in the NASA Strategic Technology Investment Plan (STIP).[4] The Agency has developed a comprehensive set of roadmaps[5] that correspond to 15 different technology areas. Within these areas are hundreds of detailed taxonomies that map directly to current NASA projects or to potential future investments. As described in the STIP, each of these elements has been placed into one of three categories: "Mission Critical," which are technologies that are required for planned or proposed missions; "Mission Enhancing," which are technologies that significantly improve mission performance; and "Transformational," which are revolutionary "over the horizon" technologies for missions yet to be conceived.

The Agency seeks to achieve a balanced portfolio of 70%-20%-10% for Mission Critical, Mission Enhancing, and Transformational technologies, respectively, and SMD aims for its technology programs to attain the same goals. NASA's STMD is an important SMD partner in this process, particularly for technology development efforts that are applicable Agency-wide. SMD refers to the Mission Critical and Mission Enhancing categories as "Mission Pull," while the Transformational category is described as "Push." The figure on page 36 roughly depicts the alignment of SMD and STMD technology programs with regard to development of "Mission Pull" and "Push" technologies.

SMD strives to invest in technologies that support the needs of its four science divisions. Effective technology development requires careful analysis of technology gaps, identification of technologies to fill those gaps, sustained investment to advance the chosen technologies, and successful infusion into missions or other products. SMD divisions receive guidance from the National Academies' decadal surveys and the science community 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 or space platforms with new or increased capabilities. Each SMD division accomplishes its technology development via competed opportunities offered through low- to mid-stage technology development programs (typically for technologies at TRLs 1-6) or via later-stage directed or competed flight programs (typically for technologies at TRLs 7-9). SMD divisions establish their own technology development programs to actively manage technology development efforts that are implemented outside of flight programs, thus ensuring progress and value are achieved for the directorate's investments. SMD's competed opportunities vary; some request ideas for development, while others are in response to a specific set of division requirements. However, all competed technology development opportunities

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[3] 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).

[4] The NASA Strategic Technology Investment Plan 2017 is available online at https://www.nasa.gov/offices/oct/home/sstip.html.

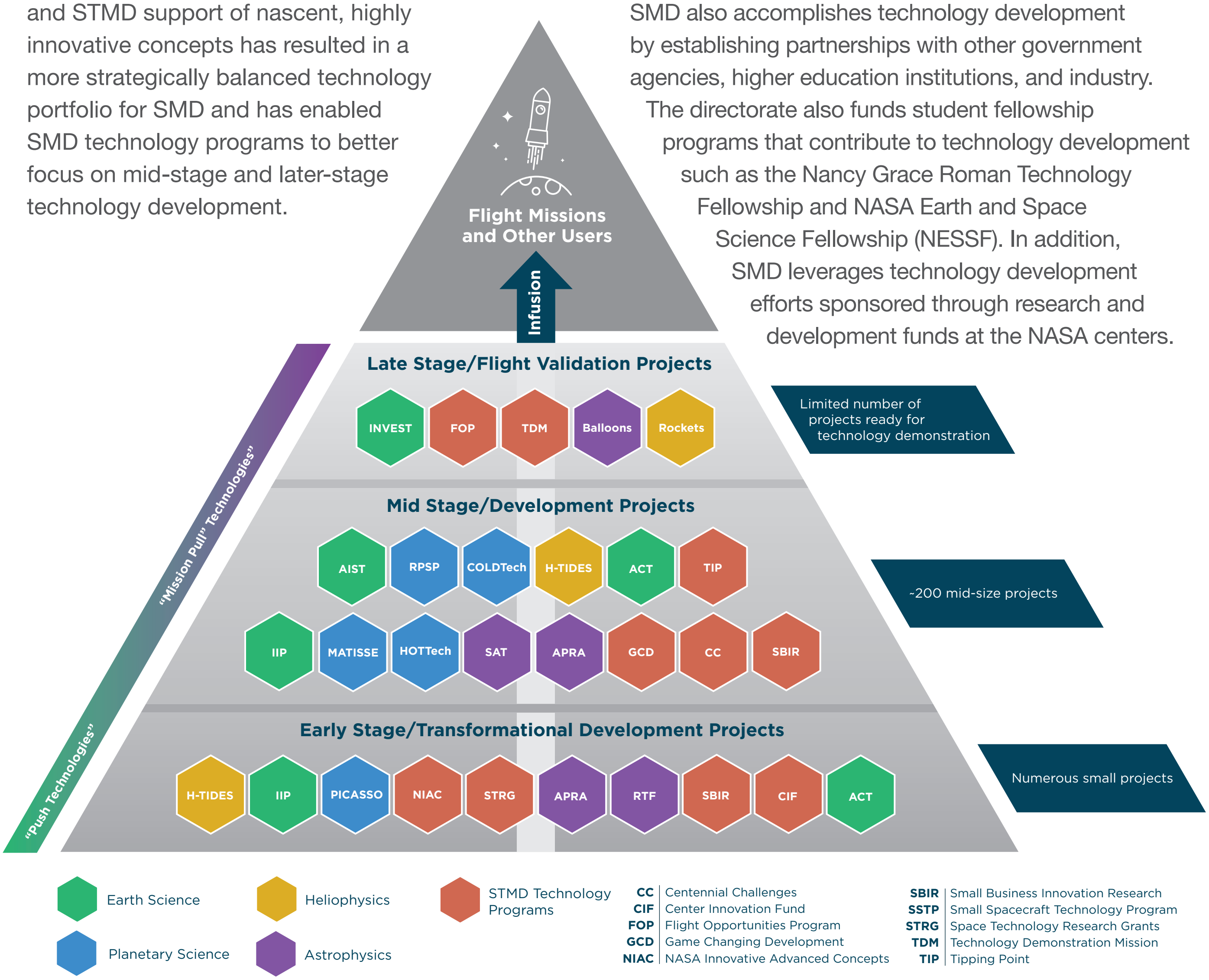
[5] The 2015 NASA Technology Roadmaps are available online at https://www.nasa.gov/offices/oct/home/roadmaps/index.html.

within SMD employ a peer review process to determine the optimal investment strategies.

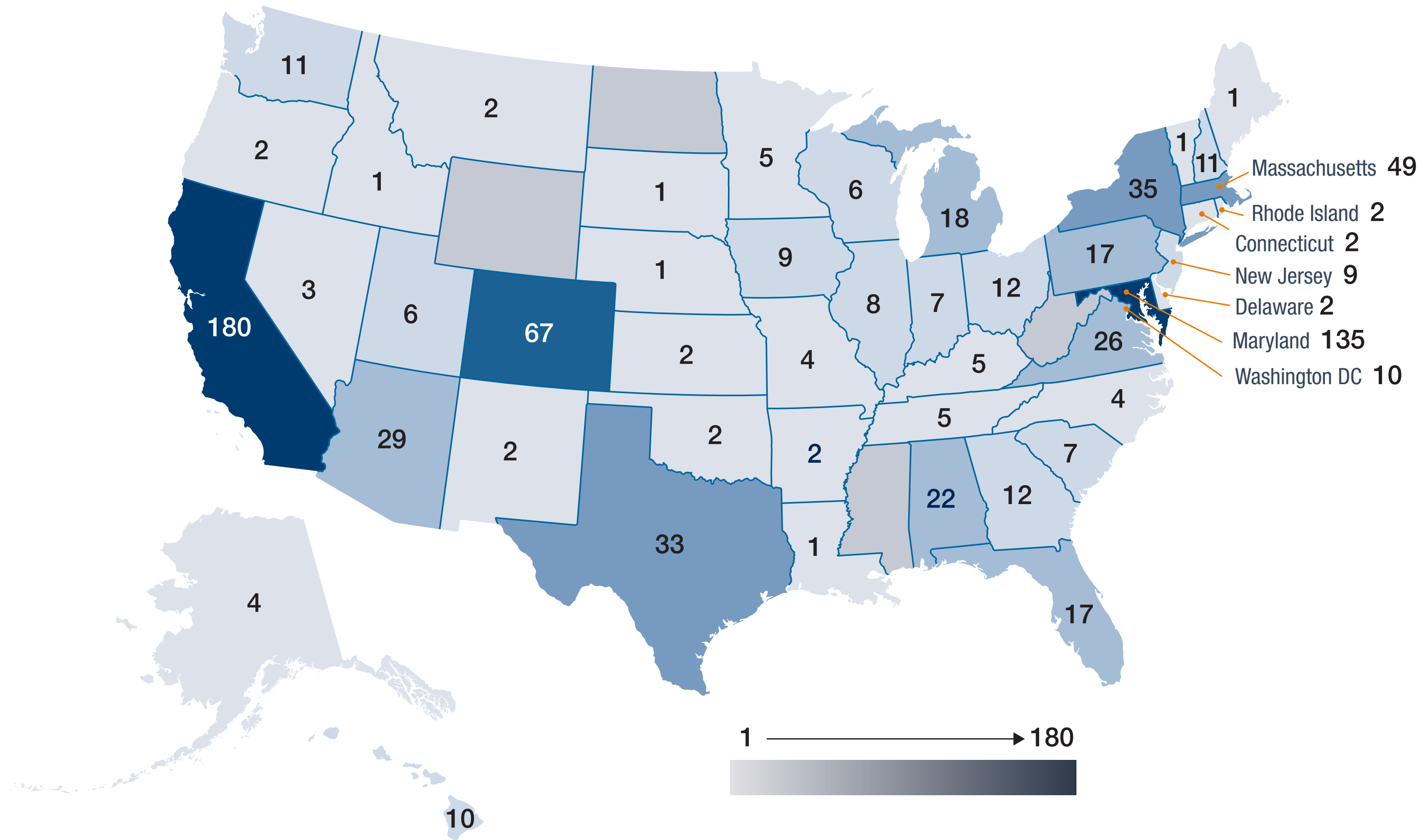
The SMD Chief Technologist also reviews the Agency technology roadmaps to determine if any of the technology needs identified elsewhere in the Agency complement SMD technology needs. Usually these needs concern groundbreaking early-stage innovations in avionics, onboard thermal management, power, propulsion,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



SMD and STMD technology development programs sponsor projects that advance "Push" and "Mission Pull" technologies. (See the table on page 5 for a description of SMD division technology development programs.)



Locations of Principal Investigators and Co-Investigators for SMD technology projects active in 2017.

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.

In 2017, SMD technology development programs funded a broad portfolio of projects at various NASA Centers and institutions distributed throughout the United States (see map above). This report highlights a sample of these activities. Additional information about these and other SMD technology projects is available on TechPort (https://techport.nasa.gov), NASA's web-based portal designed to communicate information about technology development activities implemented throughout the Agency.

ACRONYMS

3U	3-Unit
ABoVE	Arctic Boreal Vulnerability Experiment
ACT	Advanced Component Technologies
AIST	Advanced Information Systems Technology
AITT	Airborne Instrument Transition Technology
APL	Applied Physics Laboratory
APRA	Astrophysics Research And Analysis
ARCHIMEDES	A Really Cool High Impact Method for Exploring Down Into Europan Subsurface
ASIC	Application-Specific Integrated Circuit
CANON	Controlled, Agile, And Novel Ocean Network
CARTHE	Consortium for Advanced Research on Transport of Hydrocarbon in The Environment
CLASS	Cosmology Large Angular Scale Surveyor
CMB	Cosmic Microwave Background
CO_2	Carbon dioxide
COLDTech	Concepts for Ocean Worlds Life Detection Technology
COMPASS	Compact Multi-Spectral Photometer for Space Science
DFB	Distributed-FeedBack
DNA	deoxyribonucleic acid
DS	Decadal Survey
ESA	European Space Agency's
ETU	Engineering Test Unit
FEE	Front-End Electronics
GBM	Gamma-ray Burst Monitor
GHz	Gigahertz
GNSS	Global Navigation System Satellite
GPS	Global Positioning System
GSFC	Goddard Space Flight Center
GUSTO	Galactic/Extragalactic Ultralong-Duration Balloon Spectroscopic Terahertz Observatory
H-TIDeS	Heliophysics Technology and Instrument Development for Science
HabEx	Habitable Exoplanet Imaging Mission
HEEET	Heatshield for Extreme Entry Environment Technology
HOTTech	Hot Operating Temperature Technology
HSI	High-Speed Interferometer
ICON	Ionospheric Connection Explorer
IIP	Instrument Incubator Program
INCA	Ionospheric Neutron Content Analyzer
INVEST	In-Space Validation of Earth Science Technologies
JAXA	Japan Aerospace Exploration Agency
JHU	Johns Hopkins University
JHU/APL	Johns Hopkins University Applied Physics Laboratory
JPL	Jet Propulsion Laboratory
JWST	James Webb Space Telescope
KISS	Keck Institute for Space Studies
LAPD	Large Plasma Device
LBH	Lyman-Birge-Hopfield
LISA	Laser Interferometer Space Antenna
LLNL	Lawrence Livermore National Laboratory
LO	Local Oscillator
LUVOIR	Large Ultraviolet/Optical/Infrared Surveyor

ACRONYMS

MatISSE	Maturation of Instruments for Solar System Exploration
MCP-PMT	Micro-Channel Plate Photomultipliers
MEGANE	Mars-Moon Exploration with Gamma rays And Neutrons
MIT	Massachusetts Institute of Technology
MMX	Martian Moons eXploration
NESSF	NASA Earth and Space Science Fellowship
NIST	National Institute of Standards and Technology
NMSU	New Mexico State University
OCE	Office of the Chief Engineer
OCO-2	Orbiting Carbon Observatory-2
OCT	Office of the Chief Technologist
PI	Principal Investigator
PICASSO	Planetary Instrument Concepts for the Advancement of Solar System Observations
QCL	Quantum-Cascade Lasers
R&A	Research and Analysis
RAVAN	Radiometer Assessment using Vertically Aligned Nanotubes
RF	Radio Frequency
RO	Radio Occultation
RPSP	Radioisotope Power System Program
RTF	Roman Technology Fellowships
S5	Starshade to TRL 5
SAFIR	Single Aperture Far-Infrared Observatory
SALMON	Stand Alone Mission of Opportunity Notice
SAT	Strategic Astrophysics Technology
SBIR	Small Business Innovation Research
SiPM	Silicon Photomultiplier
SMAP	Soil Moisture Active Passive
SMD	Science Mission Directorate
SoilSCAPE	Soil moisture Sensing Controller And Optimal Estimator
SPLASH	Submesoscale Processes and Lagrangian Analysis on the Shelf
ST7-DRS	Space Technology 7 Disturbance Reduction System
STIP	Strategic Technology Investment Plan
STMD	Space Technology Mission Directorate
SWAP	Size, Weight, And Power
SWOT	Surface Water and Ocean Topography
TCOR	Technology Development for Cosmic Origins Program
TDEM	Technology Development for Exo-Planet Missions
TES	Transition Edge Sensor
THz	Terahertz
TIMED	Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics
TPCOS	Technology Development for Physics of the Cosmos
TPS	Thermal Protection System
TRICE-2	Twin Rockets to Investigate Cusp Electrodynamics II
TRL	Technology Readiness Level
TRYAD	Terrestrial RaYs Analysis and Detection
UCLA	University of California, Los Angeles
UMBC	University of Maryland, Baltimore County
USRA	Universities Space Research Association
VUV	Vacuum Ultraviolet
WFIRST	Wide Field Infrared Survey Telescope
WSN	Wireless Sensor Network

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