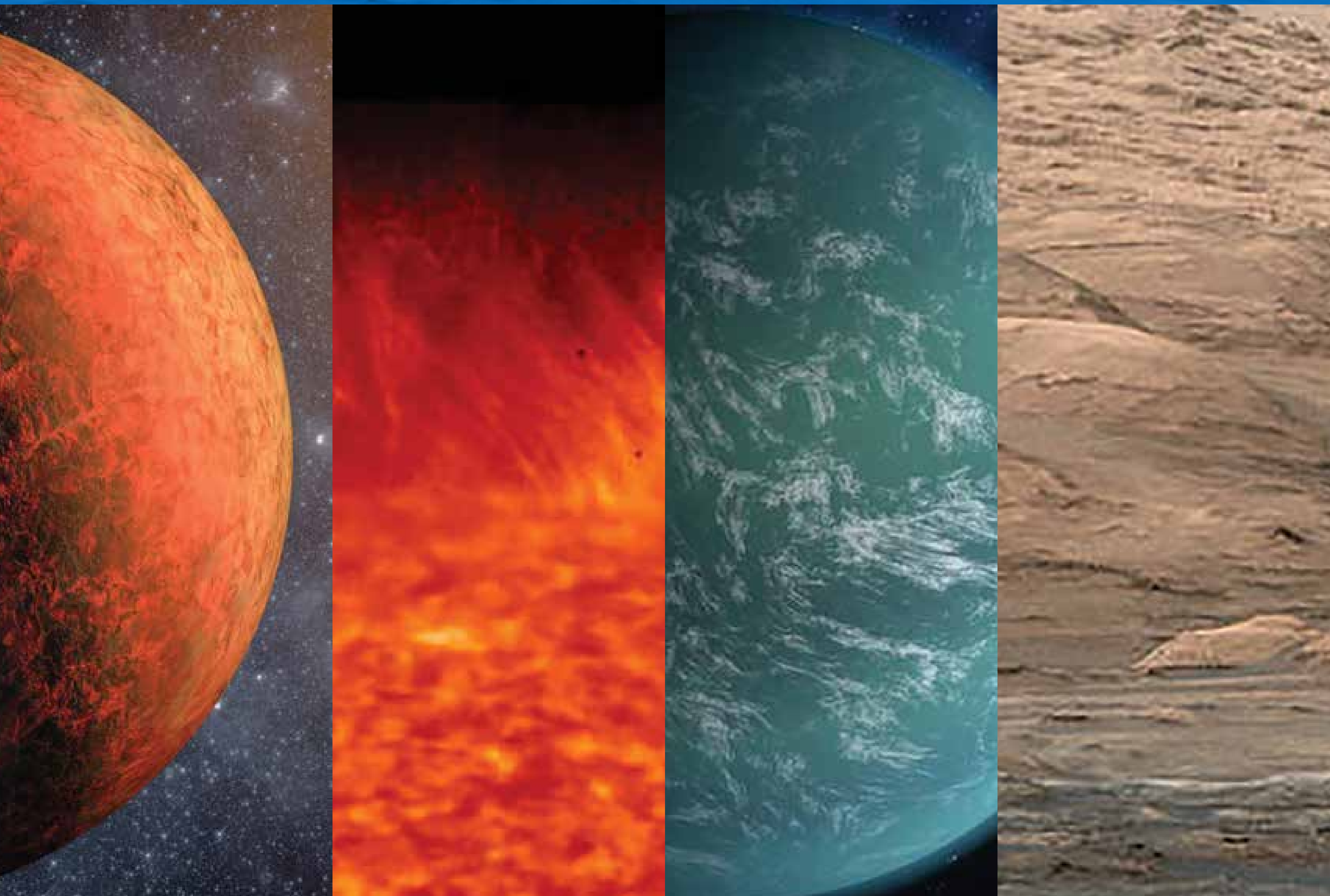
National Aeronautics and Space Administration

2014 | SCIENCE MISSION DIRECTORATE
Technology Development Report



Introduction 04

2014 Technology Development Highlights 07

Systems and Subsystems 07

Unlocking the Mysteries of the Universe: Enabling WFIRST to Study Dark Energy 07

Imaging Giant Exoplanets Around Nearby Stars 08

Detecting Climate Change Faster 09

Improving Altimeter Measurements to Enable Monitoring of Coastal and Inland Waters 10

Opening a Window into the Unknown 11

Rockets, Power, and Propulsion 12

Powering Spacecraft and Instruments to Explore the Solar System 12

Designing a New Rocket to Enhance Science Return 13

Data Validation 14

Studying Carbon: A Piece of the Climate Change Puzzle 14

2014 Technology Infusion Highlights 15

Missions 15

SMD Technology Investments Enable SMAP Mission 15

Mars 2020 Instruments Will Use New Technology to Explore the Red Planet 17

2014 Discovery Announcement of Opportunity Enables Technology Infusion 19

NuSTAR Discovers Rare and Mighty Pulsar 21

Systems and Subsystems 22

Innovative Antenna Mast Will Facilitate Oceanographic and Hydrologic Science “Firsts” 22

Balloon Flights Demonstrate New Astrophysics Technologies 23

High-flying Spectrograph Enables Unique Astronomical Data Collection Capability 24

Rockets, Power, and Propulsion 25

Enhanced Radioisotope Thermoelectric Generator Will Provide Missions with Increased Power 25

Appendix A. The SMD Technology Development Strategy 26

INTRODUCTION

The role of the Science Mission Directorate (SMD) is to enable NASA to achieve its science goals in the context of the National science agenda. SMD's strategic decisions regarding future missions and scientific pursuits are guided by Agency goals, input from the science community—including the recommendations set forth in the National Research Council (NRC) decadal surveys—and a commitment to preserve a balanced program across the major science disciplines. Toward this end, each of the four SMD science divisions—Heliophysics, Earth Science, Planetary Science, and Astrophysics—develops fundamental science questions upon which to base future research and mission programs (see sidebar). Often the breakthrough science required to answer these questions requires significant technological innovation—e.g., instruments or platforms with capabilities beyond the current state of the art. SMD's targeted technology investments fill technology gaps, enabling NASA to build the challenging and complex missions that accomplish groundbreaking science.

The directorate works to ensure that NASA actively identifies and invests in the right technologies at the right time to enable the Agency's science program. SMD technology development is part of a comprehensive Agency-wide strategy that involves coordination with the NASA Chief Technologist and other Agency mission directorates. This coordination helps ensure that crosscutting technology development needs are identified across the Agency and that there is optimal return on investments to fulfill those needs. SMD accomplishes technology development through technology programs established in each of its four science divisions. (See table

SMD Division Fundamental Science Questions

Heliophysics

- What causes the Sun to vary?
- How do the geospace, planetary space environments and the heliosphere respond?
- What are the impacts on humanity?

Earth Science

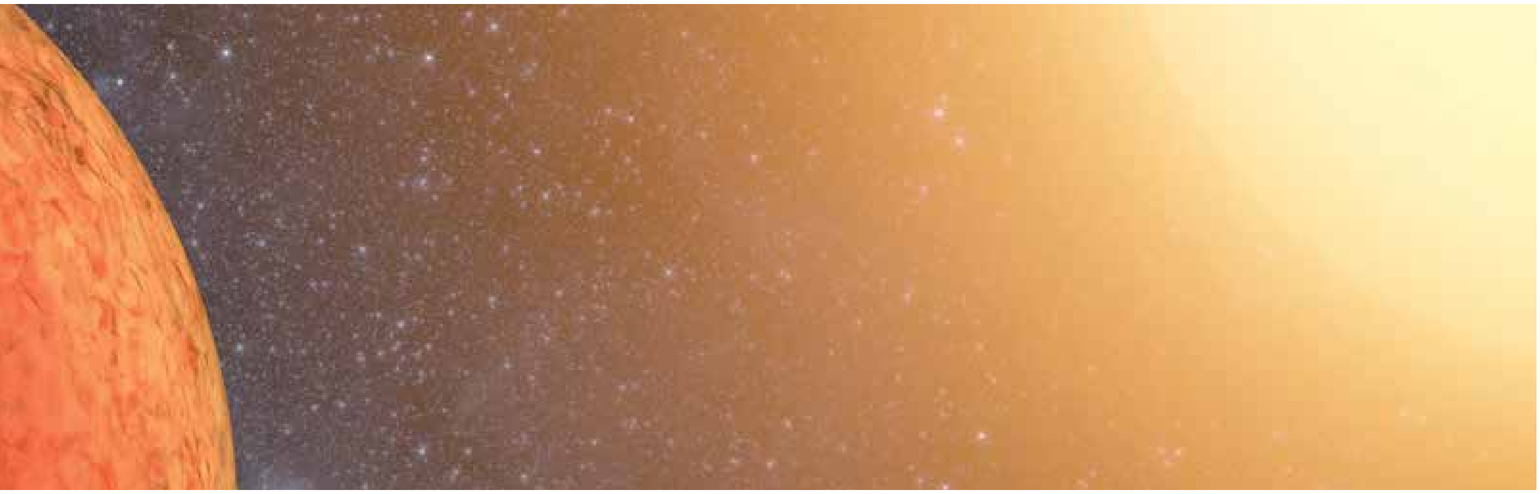
- How is the global Earth system changing?
- What causes these changes in the Earth system?
- How will the Earth system change in the future?
- How can Earth system science provide societal benefit?

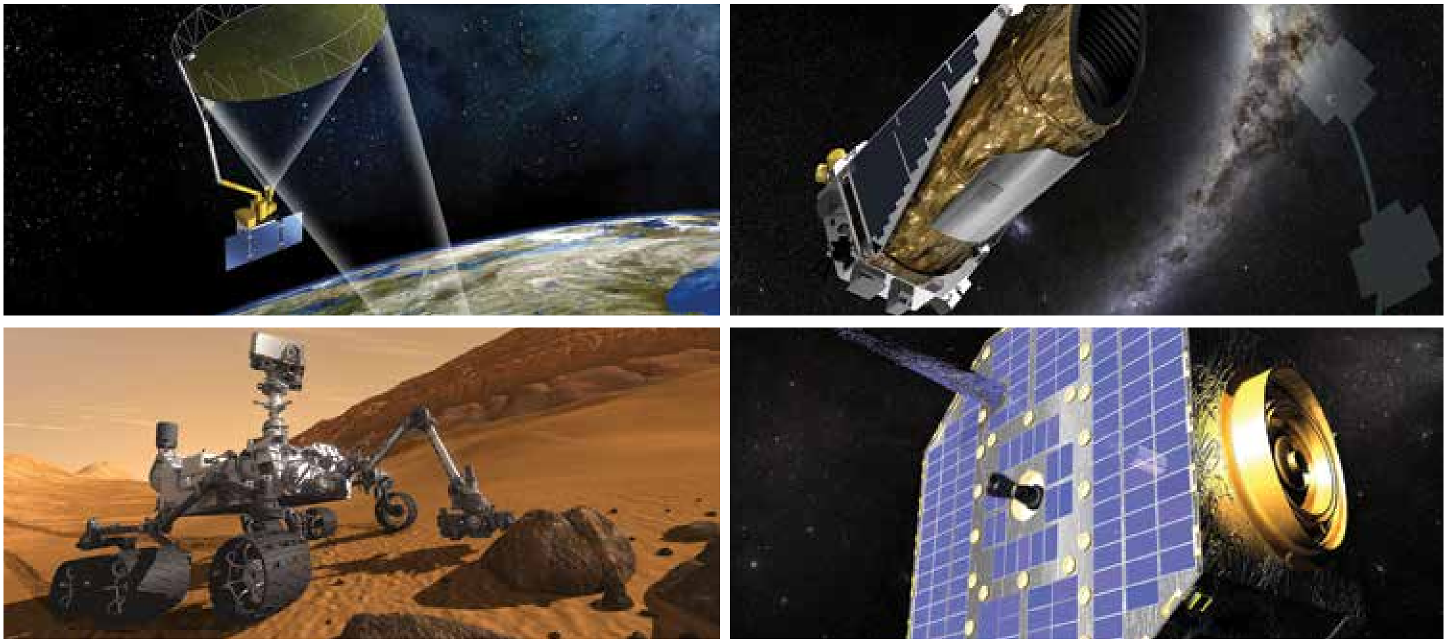
Planetary Science

- How did our solar system form and evolve?
- Is there life beyond Earth?
- What are the hazards to life on Earth?

Astrophysics

- How does the universe work?
- How did we get here?
- Are we alone?





NASA missions in all four science areas have benefitted from SMD technology development investments (Clockwise from top left: SMAP, Kepler, IBEX, MSL Curiosity Rover)

on next page for a list of SMD technology development programs.) If a technology development effort reaches a high enough Technology Readiness Level (TRL), it may be infused into an SMD flight program and targeted for further maturation, enabling its use for a specific mission application.

The second chapter of this report highlights the most significant SMD technology development efforts of 2014. The third chapter briefly describes recent SMD technology infusion efforts—i.e., technologies that have been transferred to the technology user (typically a flight mission) for refinement and eventual application.

Appendix A briefly reviews SMD's technology strategy and technology development process, including the feedback loop that ensures the science community both informs SMD technology investment decisions and is informed about SMD technology developments.

SMD TECHNOLOGY DEVELOPMENT PROGRAMS

Earth Science Division (funded and managed through the Earth Science Technology Office, ESTO)	
Advanced Component Technologies (ACT)	Develops a broad array of 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)	Develops low- to medium-TRL technologies, as well as instrument feasibility studies and proof of concept efforts.
Planetary Science Division	
Planetary Instrument Concepts for the Advancements of Solar System Observations (PICASSO)	Funds the development of low-TRL technologies (TRL 1-4) leading directly to the development to 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.
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).

2014 TECHNOLOGY DEVELOPMENT HIGHLIGHTS

SYSTEMS AND SUBSYSTEMS

Unlocking the Mysteries of the Universe: Enabling WFIRST to Study Dark Energy

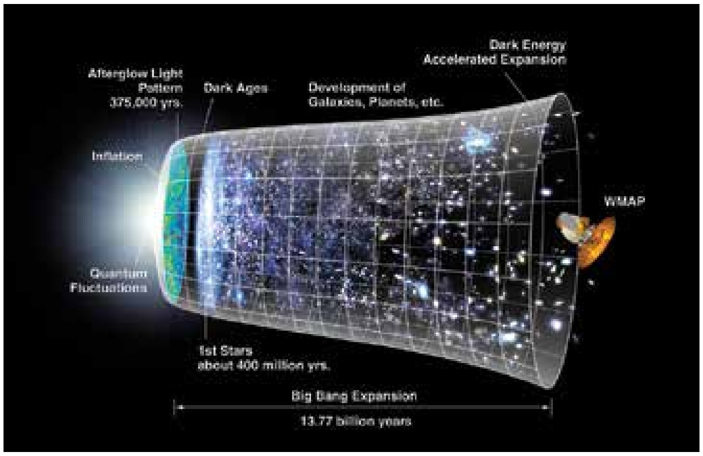
Critical Detector Technology for the WFIRST-AFTA Mission Reaches Milestone

Technology: The H4RG-10 near-infrared detector is a critical technology enabling the Wide-Field Infrared Survey Telescope (WFIRST)—the highest-ranked recommendation for a large space mission in the NRC 2010 decadal survey, New Worlds, New Horizons (NWNH) in Astronomy and Astrophysics. Developed by Teledyne Imaging Sensors, the 16-megapixel H4RG-10 detector employs a 4096×4096 array of 10-micron pixels. This technology provides four times as many pixels as the previous generation of detectors in a package that is only slightly larger, permitting greater coverage at reduced cost.

The H4RG-10 detector

Impact: The H4RG-10 detector is an enabling component of the WFIRST-AFTA (Astrophysics Focused Telescope Assets) mission concept, which aims to address the high-priority science objectives identified for WFIRST in the NWNH survey. During its five year mission, WFIRST-AFTA will enable the study of dark energy, monitor stars in the central Milky Way for gravitational microlensing events to help discover exoplanets, survey the near infrared sky, and enable the study of galaxy formation, structure, and growth. With eighteen H4RG-10 detectors in a single focal plane, WFIRST-AFTA's imager will cover 0.28 deg^2 of sky in a single image at a pixel scale of 0.11 arcsec/pixel.

Status and Future Plans: In December 2014, H4RG-10 detectors were successfully demonstrated at NASA's TRL 6—a key milestone for acceptance into space missions. This important technology achievement is a broadly enabling technology for astrophysics with a breadth of potential applications, not only for large space missions such as WFIRST-AFTA, but also for Explorer-class near-infrared missions and other ground- and space-based astrophysics programs.

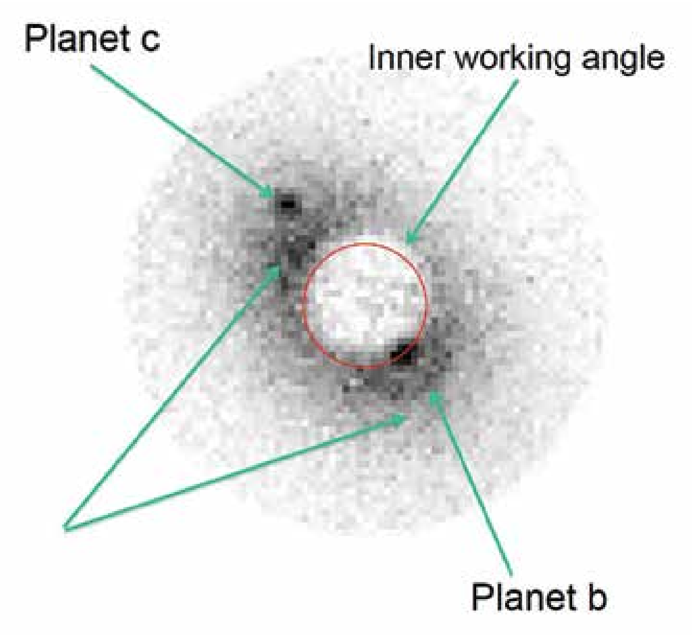


This representation of the evolution of the universe shows the effects of dark energy. The far left depicts the earliest moment we can now probe, when a period of "inflation" produced a burst of exponential growth in the universe. (Size is depicted by the vertical extent of the grid in this graphic.) For the next several billion years, the expansion of the universe gradually slowed down as the matter in the universe pulled on itself via gravity. More recently, the expansion has begun to speed up again as the repulsive effects of dark energy have come to dominate the expansion of the universe. (Image credit: NASA/WMAP Science Team)

Sponsoring Organization: The Astrophysics Division funds this technology via the SAT program.

Imaging Giant Exoplanets Around Nearby Stars
WFIRST-AFTA Coronagraph Will Enable First Reflected-light Visible Images

Technology: After evaluating various coronagraph technologies as part of the WFIRST-AFTA mission study, NASA announced the selection of the Occulting Mask Coronagraph in December 2013. This coronagraph includes both a Shaped Pupil Coronagraph (SPC) and a Hybrid Lyot Coronagraph (HLC). To achieve the required starlight suppression with the obscured 2.4 meter AFTA telescope, however, new design and fabrication approaches had to be developed for the instrument.



Simulated WFIRST-AFTA coronagraph image of the 47 UMa planetary system, including planets and the exozodiacal disk. The WFIRST-AFTA coronagraph will provide the first reflected-light visible images of the planetary systems of nearby stars.

Impact: The WFIRST-AFTA coronagraph will be the first high-contrast stellar coronagraph in space. It will enable WFIRST-AFTA to respond to the goals of NWNH by directly imaging and spectrally characterizing giant exoplanets similar to Neptune and Jupiter, and possibly even super-Earths (extrasolar planets with a mass higher than Earth's but lower than our Solar System's ice giants, Neptune and Uranus), around nearby stars. It will also provide important information on the physics of planetary atmospheres by measuring the exozodiacal disk level (warm debris disks) around nearby stars, imaging circumstellar disks for signals of planet interactions, and furthering our understanding of planetary system formation. Finally, development of the WFIRST-AFTA coronagraph will help mature critical technologies (common to many types of coronagraphs), while informing the future technology downselect for a later terrestrial-planet imaging mission.

Status and Future Plans: Excellent progress was achieved in maturing both the coronagraph technology and the WFIRST-AFTA coronagraph design in 2014. NASA Jet Propulsion Laboratory's (JPL) MicroDevices Lab (MDL) and Caltech's Kavli Nanoscience Institute processed black silicon for the coronagraph, producing some of the darkest surfaces in the world with specular reflectance of less than 1 part in 10 million. NASA-sponsored projects demonstrated that the WFIRST-AFTA coronagraph satisfies certain aspects of the broader exoplanet technology program recommended by NWNH by developing and demonstrating advanced coronagraph starlight suppression techniques, and advancing wavefront-controlled coronagraph technology toward flight-ready levels. Continuing this momentum, the FY 2015 President's Budget Request contains, for the first time, an explicit line item for the above activities, to fund the "ongoing study of a possible WFIRST-AFTA mission, the next major observatory beyond the James Webb Space Telescope (JWST), for a potential start of formulation activities later this decade."

Sponsoring Organization: Initially funded by the Astrophysics Division's SAT program, this technology is now being jointly developed in partnership with the NASA Space Technology Mission Directorate (STMD).

Detecting Climate Change Faster

HySICS HyperSpectral Imager Collects Highly Accurate Earth-reflected Radiation Measurements

Technology: On August 8, 2014 the HyperSpectral Imager for Climate Science (HySICS) instrument successfully demonstrated its capability to take science measurements—possibly providing the most accurate measurements of outgoing Earth-reflected radiation ever made. During the experiment, a high-altitude balloon carried HySICS 122,000 feet over Fort Sumner, New Mexico, above most of the Earth's atmosphere to reach space-like conditions. During the nearly 9-hour flight, HySICS collected measurements in the ultraviolet-to-infrared region (350-2300nm), cross-calibrating the data by making periodic measurements of the Sun. Self-calibration against the Sun's known emitted energy provided the instrument with a reference point, allowing it to collect such accurate data from Earth.

A NASA high-altitude balloon is inflated with helium in preparation for the HySICS science demonstration flight. (Image: NASA Balloon Program Office.)

Impact: Scientists use outgoing shortwave radiance, or the amount of sunlight scattered from Earth's surface and atmosphere and reflected back toward space, as one of the key metrics for studying our planet's dynamic climate. Achieving radiance measurements of this accuracy was identified by the 2007 NRC Earth Science Decadal Survey as critical to Earth climate science. NASA's Earth-observing satellites have collected Earth radiance measurements for years, but the highly accurate measurements from HySICS will enable faster detection—in years instead of decades—of climate trends than previous radiance data allow.

Status and Future Plans: The HySICS project successfully demonstrated a single focal plane array spectrometer, providing data spanning the desired wavelength range—with increased accuracy, and at reduced mass, volume, power, and cost than previous instruments. This important technology achievement may enable a new generation of spaceborne instruments that will collect the accurate data scientists need to create more reliable climate models.

Sponsoring Organization: The Earth Science Division provided Principal Investigator (PI) Greg Kopp of the Laboratory for Atmospheric and Space Physics (LASP) at the University of Colorado Boulder with funding to develop HySICS through the ESTO 2010 IIP solicitation.

Improving Altimeter Measurements to Enable Monitoring of Coastal and Inland Waters

HAMMR—a New Airborne Radiometer—Conducts Its First Flights

Technology: Current sea surface height altimeter missions utilize microwave radiometers operating at cm wavelengths to correct for measurement errors due to changes in humidity between the satellite and the sea surface. If humidity in the atmosphere is not accurately characterized, it skews the data enough to make sea surface height measurements inaccurate, an error known as wet-path delay. HAMMR, the High-frequency Airborne Microwave and Millimeter-wave Radiometer, measures the wet-path delay with much higher spatial resolution than current capabilities allow, and is designed to demonstrate a high-frequency millimeter-wave radiometer capability that can be directly integrated into future altimetry space missions. HAMMR incorporates the currently used cm-wavelength microwave channels (18.7, 23.8 and 34.0 GHz) and provides enhanced capability by adding higher frequency millimeter (mm)-wavelength channels at 90, 130, and 166 GHz.

In July 2014, HAMMR made extensive engineering flights over Utah's Lake Powell—a large inland body of water with a number of clear land-to-water transitions. The inset map shows one of the flight lines over Lake Powell. (Image: Google Earth.)

Impact: Currently used cm-wavelength radiometers can only provide valid measurements over large water bodies, such as oceans. These instruments cover a large measurement area, or footprint, on the surface, causing errors within 25 to 50 km from the coasts, a key zone for marine activity and aquatic life, where reliable sea surface height measurements are critically needed. This large footprint also makes it difficult to accurately study the height of inland bodies of water, such as lakes and rivers, which are typically much smaller than the radiometer measurement area. HAMMR's mm-wavelength capability will enable better wet tropospheric path delay corrections, which can greatly improve the performance of radar altimetry. In addition, HAMMR's footprint is smaller than currently used radiometers, which enables accurate measurements in coastal areas and inland bodies of water.

Status and Future Plans: HAMMR completed its first engineering flights onboard a Twin Otter aircraft in early July 2014. These flights served to check out the performance of the instrument and included flight paths that involved a number of land-to-water transitions. In the future, scientists could use data from HAMMR to test algorithms that apply wet-path delay corrections closer to the world's coastlines and explore the potential for enabling more accurate error correction over inland water. HAMMR could eventually be used to perform regular regional high-resolution wet-path delay measurements along coasts and over small rivers and lakes, which would provide scientists with a better understanding of water surface height and sea level changes. HAMMR may also serve as an airborne calibration and validation instrument in support of the Surface Water and Ocean Topography (SWOT) mission—a mission recommended by the 2007 NRC Earth Science Decadal Survey.

Sponsoring Organization: The Earth Science Division provided funding via an IIP solicitation to PI Steven Reising of Colorado State University to develop this technology in collaboration with JPL and the University of California, Los Angeles.

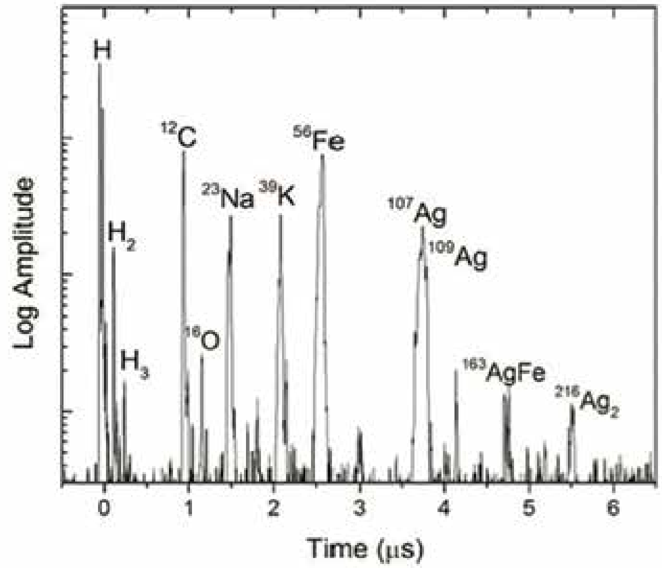
Opening a Window into the Unknown
Exploring Nanometer-Sized Dust in the Solar Wind

Technology: One of the big surprises of the NASA/ Heliophysics Solar Terrestrial Relations Observatory (STEREO) mission launched in 2006 was the discovery of nanometer-sized dust particles present in the solar wind. These particles were unexpectedly detected as a background signal by the wave antenna instruments on the STEREO spacecraft. While micrometer-sized dust has been known for some time, very little is known about the source, nature, and occurrence rate of the nanodust population, which have diameters ~1,000 times smaller than micrometer-sized particles. The apparent radial speed of nanodust particles seems driven by and can almost be as high as the solar wind itself. The goal of the Nano Dust Analyzer (NDA) project was to develop a dust chemical analyzer instrument to detect and analyze nanometer-sized dust particles originating from the inner solar system. The concept of the instrument design was derived from the experiences gained from previous dust detector and analyzer instrument efforts, including, for example, the Cosmic Dust Analyzer (CDA) on Cassini, or the Lunar Dust Experiment (LDEX) on the Lunar Atmosphere and Dust Environment Explorer (LADEE). The figure below shows the most suitable design for the Nano Dust Analyzer.

The laboratory prototype of the NDA instrument

Impact: This detector can potentially provide analysis of the chemical and dynamical properties of these dust particles, opening a new window of understanding into Heliophysics processes. Potential sources of nanometer-sized dust can be comets, asteroids, interstellar dust, the interaction of larger dust particles with the surfaces of planets and moons, and admixtures of solar wind or solar particles. Chemical analysis would provide insight into the source(s) of these particles. More generally, dust in the heliosphere can influence space weather at Earth and at other locations in the heliosphere out to the interstellar medium.

Status and Future Plans: Designing the NDA instrument to operate under harsh solar ultraviolet (UV) illumination was one of the most challenging tasks of this project. Nanodust particles arrive at Earth's orbit from directions close to Sun pointing. UV photons thus will enter the instrument and can scatter into the ion detector and contribute to background noise and/or reduce the lifetime of the instrument. The instrument design has been optimized through inclusion of baffles, innovative coating, and geometry adjustments so that the number of UV photons scattering into the detector are reduced well below the requirement. Given the recent discovery of this phenomenon, there are not yet any Heliophysics mission plans that identify the inclusion of a fully developed nano-dust instrument as a science priority. However, the Heliophysics Explorer program and the recently established CubeSat opportunity would offer venues for addressing the science behind nano-dust particles in the near term.



A sample mass spectrum measured by the NDA instrument using the dust accelerator facility at the University of Colorado.

Sponsoring Organization: The Heliophysics Division's H-TIDeS program funded this project, led by Eberhard Grün at the University of Colorado.

ROCKETS, POWER, AND PROPULSION

Powering Spacecraft and Instruments to Explore the Solar System

NASA Continues Development of Radioisotope Power Systems

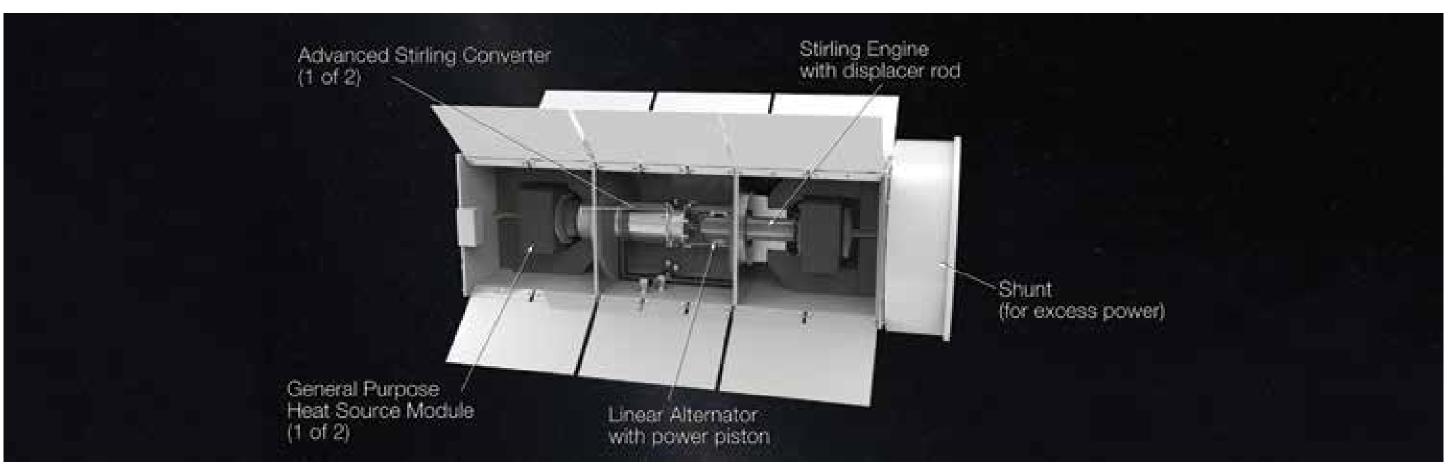
Technology: The NRC's 2011 decadal survey, "Vision and Voyages for Planetary Science in the Decade 2013-2022," articulates the continuing need for NASA planetary science missions to achieve scientific goals. Radioisotope Power Systems (RPS) are critical to planetary missions because they are capable of producing electricity and heat for decades under the harsh conditions of deep space without refueling. Implementation of nuclear systems, however, has never been an easy task. In 2014, NASA chartered the Nuclear Power Assessment Study (NPAS) to examine the Agency's approach to provisioning nuclear power systems—including the RPS that power SMD missions and the Fission Power Systems (FPS) that typically could support Human Exploration and Operations Mission Directorate (HEOMD) missions. The objective of NPAS was to discuss a sustainable strategy and present findings for the provisioning of safe, reliable, and affordable nuclear power systems that enable SMD missions and are extensible to HEOMD needs in the next 20 years.

Impact: The NPAS team concluded that nuclear power systems remain essential to enable the high-priority mission concepts recommended by the decadal survey. The power levels required for such missions are less than 1 kWe and are best met by RPS solutions. Sustaining this capability requires plutonium production and funding of the maintenance of the associated infrastructure by NASA. Due to the size of foreseen FPS concepts, the NPAS results also indicated that FPS does not represent a good fit for the currently projected SMD missions, but has promise for HEOMD surface missions. To meet SMD science needs across mission classes, the availability of both thermoelectric and Stirling converters to support RPS appears to be advantageous for the foreseeable future. In fact, the NPAS results indicated that among the options considered, Stirling systems offer the highest efficiency, which will help conserve the limited plutonium supply.

RPS have enabled numerous NASA missions over the last five decades, including the Mars Science Laboratory launched in November 2011. The Curiosity rover took this image showing its Multi-Mission Thermoelectric Generator (MMRTG) on the surface of Mars on Aug. 7, 2012.

Status and Future Plans: In 2014, the RPSP began investing in the technology maturation of skutterudite-based thermoelectric couples targeted for integration into an enhanced Multi Mission Radioisotope Thermoelectric Generator (eMMRTG)—see page 25. NASA also began to formulate the plan forward for the development of a future Stirling-based RPS to be delivered in the late 2020s. NASA intends to continue development of this advanced technology for potential integration into flight systems that will enable the planetary science missions of the future.

Sponsoring Organization: The Planetary Science Division's RPSP performed the NPAS in collaboration with at least five NASA centers, the Department of Energy (DOE) and its laboratories, the Johns Hopkins University Applied Physics Laboratory, and independent consultants.



Radioisotope generator based on the free-piston Stirling converter design developed by Sunpower, Inc. The device is approximately 0.3m long. (Image Credit: NASA JPL)

Peregrine vehicle configurations

Designing a New Rocket to Enhance Science Return

Peregrine Rocket Motor Progresses Toward Flight Tests

Technology: NASA is developing new technology that will facilitate one of the Agency's most robust, versatile, and cost-effective flight programs—the NASA Sounding Rocket Program. Sounding rockets enable scientific experimentation and engineering tests in space for very low cost compared to Earth-orbiting platforms. The goal of the Peregrine project is to develop and demonstrate a new sustainer stage and associated designs to support all the stage configurations utilized in the Sounding Rocket Program. The need to embark in this risk mitigation effort was driven by technical and delivery issues with the sustainer motors the program currently uses. The Peregrine is a 20 inch diameter sustainer motor 18.6 feet in length with 2,950 pounds of propellant.

Impact: The Peregrine design and manufacturing process result in several benefits. Peregrine has a larger diameter than the heritage motor, allowing it to deliver more impulse and increased vehicle performance, resulting in an enhanced science return. The larger motor also enables larger payload designs that improve carrier capabilities. The motor case is constructed from readily available 4130 steel, which keeps costs low and maximizes durability. The Peregrine fabrication process strain-hardens the case as it is flow-formed over a mandrel. Since a thick weld land is used to reduce stress, the case can be constructed without a complex heat treatment on the finished assembly. Eliminating the heat treatment process reduces design complexity, resulting in schedule and economic benefits. The Peregrine is the first flow-form fabricated motor case of this magnitude. The Peregrine employs a pyrogen igniter—a first for the Sounding Rocket Program—that was designed, developed, and fabricated in house at Marshall Space Flight Center (MSFC). Not only will the pyrogen igniter improve ignition consistency and reliability, a unique feature on the Peregrine measures both igniter pressure and motor pressure to provide redundant measurements to help characterize performance.

Open air igniter test at MSFC

Status and Future Plans: Hydro proof testing was conducted on the prototype design and NASA successfully conducted an open-air ignition test in mid-2014. The Peregrine project also completed extensive hardware fabrication in 2014 (the vendor delivered motors and cases and NASA completed the test flight vehicle hardware) and conducted a successful hydro proof test of the case. The planned flight test program includes two launches at Wallops Flight Facility and one at White Sands Missile Range.

Sponsoring Organization: The Heliophysics Division's Sounding Rockets and Range Program sponsors the Peregrine project. Three of the four Agency mission directorates contributed to fund the Peregrine effort, and seven of the ten NASA field centers have been involved in the project.

DATA VALIDATION

Studying Carbon: A Piece of the Climate Change Puzzle

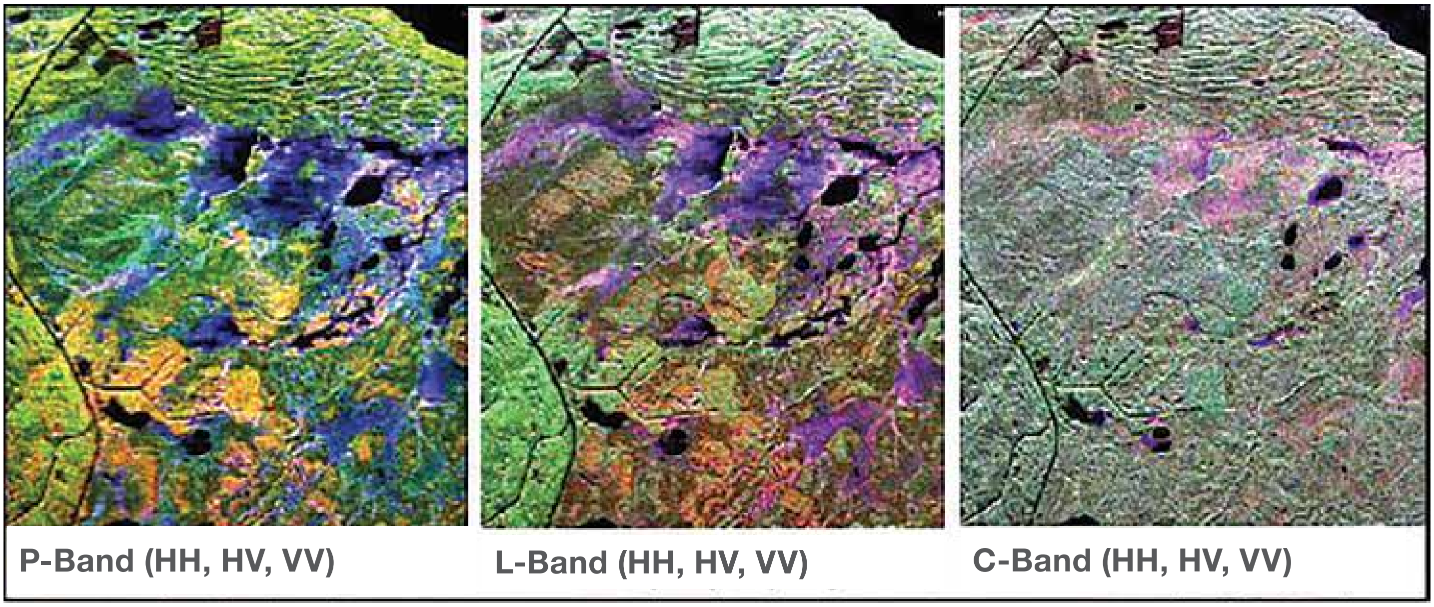
EcoSAR Gathers Improved Biomass and Ecosystem Measurements

Technology: Information about Earth's carbon cycle—the exchange of carbon among Earth's oceans, atmosphere, ecosystem, and geosphere—is essential to further our understanding of the climate changes occurring on our planet. The newly developed instrument EcoSAR has demonstrated the capability to measure Earth's carbon-storage systems faster and more accurately than other commonly employed radar instruments. EcoSAR is an airborne polarimeteric and interferometric P-band radar instrument—the first P-band radar of its kind in the U.S. EcoSAR uses two antennas mounted 25 meters apart on either wing of the aircraft. By spacing the antennas in this manner, EcoSAR is able to achieve interferometry with a single pass instead of flying repeat passes over the same area.

Impact: EcoSAR's P-band wavelength enables better measurements of the forest volume and woody density (the biomass) by allowing the instrument to penetrate more deeply into the forest canopy than the L-, C-, or X-band wavelengths more commonly employed. EcoSAR's measurements can tell researchers much about the extent of terrestrial forests and the changes to which these environments are prone, due to factors such as flooding, wildfires, and deforestation. Understanding these high-biomass ecosystems and the changes they are undergoing will give climate researchers new insights about how much carbon these environments store and how much carbon can be released as the ecosystem faces natural and human-induced changes.

Status and Future Plans: In March 2014, EcoSAR made its inaugural flights on a National Oceanic and Atmospheric Administration (NOAA) P-3 aircraft and demonstrated its ability to measure canopy height of tall forests to within 1-meter accuracy and above-ground woody biomass with 20% accuracy. In the future, the EcoSAR team plans to fly over additional ecosystems to test the instrument's capability for permafrost, ice, and snow depth measurements. It is estimated that twice the amount of carbon that is stored in the atmosphere may be found locked away in permafrost. EcoSAR may also be employed to validate future satellite missions employing SAR systems to conduct global measurement campaigns. Once fully demonstrated, EcoSAR may prove to be a valuable tool that provides highly-accurate data for use in studying climate, ecosystem changes, and atmospheric science.

Sponsoring Organization: The Earth Science Division provided funding for EcoSAR to PI Temilola Fatoyinbo at NASA Goddard Space Flight Center (GSFC) via the IIP.



Scene comparison in P-, L- and C-band observations. EcoSAR uses P-band wavelength to enable better measurements of the forest volume and woody density.

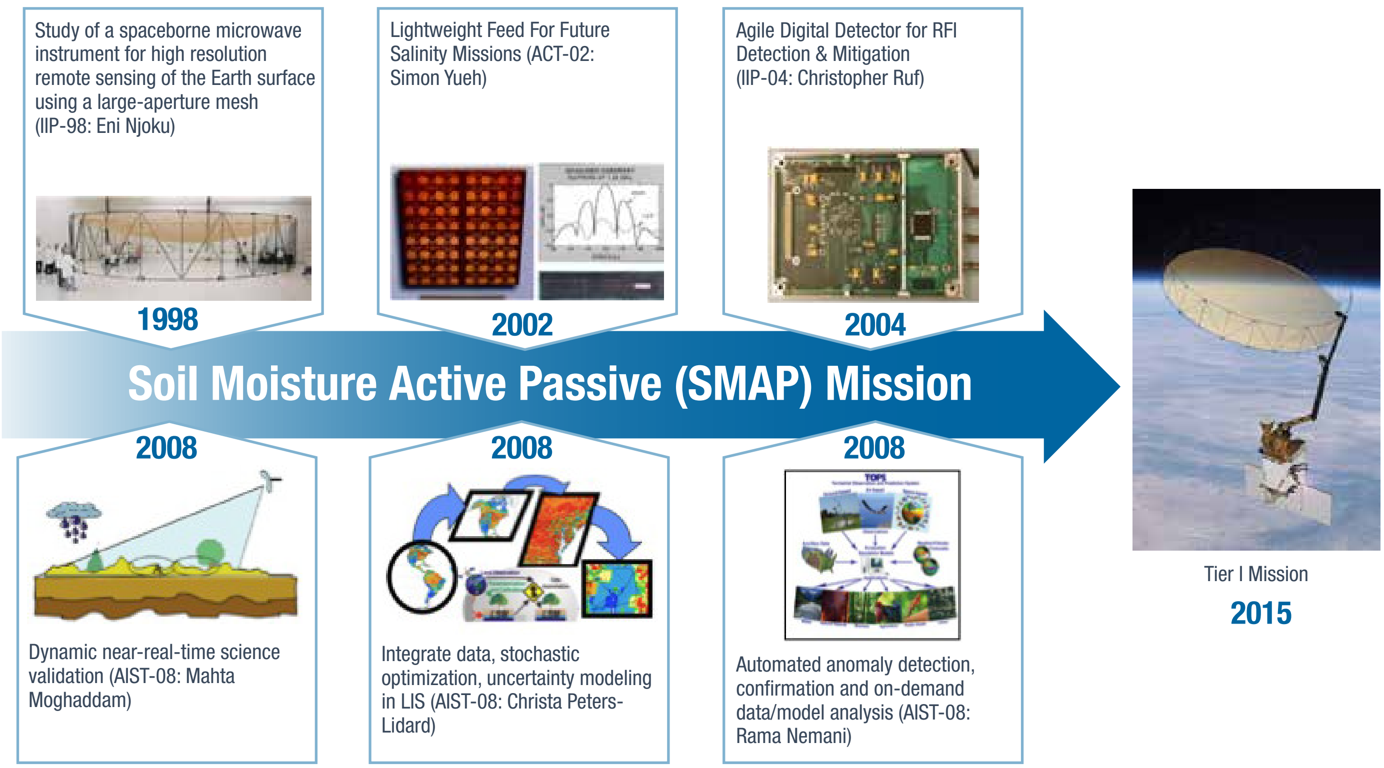
2014 TECHNOLOGY INFUSION HIGHLIGHTS

MISSIONS

SMD Technology Investments Enable SMAP Mission

SMAP to Provide Global Soil Moisture Measurements

Infusion Project: In 2014, NASA put the finishing touches on the Soil Moisture Active Passive (SMAP) satellite in preparation for its January 2015 launch. SMAP—one of four Tier-1 missions recommended in the 2007 NRC decadal survey—will measure the amount of water in the top two inches of soil everywhere on Earth's surface that is not frozen or covered with water. SMAP carries two instruments—a radar (active) and a radiometer (passive)—that share a single feedhorn and rotating mesh reflector. By employing advanced processing techniques, scientists will use both the radar observations (high spatial resolution but lower soil moisture sensitivity) and radiometer observations (higher soil moisture accuracy but coarse spatial resolution) to retrieve soil moisture data that meet the mission science requirements. Sustained SMD technology



Sustained SMD technology investment enabled the SMAP mission.

investment over 10+ years helped enable the SMAP mission, with numerous SMD technology development efforts contributing to SMAP success.

Technologies Infused: SMD invested in several technologies that led to the unique SMAP instrument concept. In 1998, Eni Nkoju of JPL led an IIP project to develop a concept for a combined passive and active sensor that used a 6-m diameter, lightweight, deployable mesh antenna—a precursor to the SMAP system. In 2002, PI Simon Yueh, also at JPL, developed a compact, lightweight, dual-frequency antenna feed. Funded through the Advanced Component Technologies (ACT) program, Yueh's system was designed to support a future soil moisture mission employing a large reflector with passive and active sensing capabilities.

SMD investments also enabled development of another important technology employed on SMAP—the capability to detect and mitigate radio frequency interference (RFI) that can potentially degrade mission science measurements. In 2004, SMD funded development of an Agile Digital Detector (ADD) to detect and mitigate RFI on spaceborne radiometers. Through this IIP project, PI Chris Ruf at the University of Michigan developed three different versions of an ADD and conducted ground and airborne field campaigns to evaluate detector performance.

As measurement capabilities advance, corresponding technology advancements are often required to interpret and apply the data. In 2008, ESTO's AIST program funded three different technology development efforts designed to maximize the value of the science measurements SMAP collects. While at the University of Michigan, PI Mahta Moghaddam led a project to develop technologies for dynamic and near-real-time validation of space-borne soil moisture measurements. This project involved development of a ground-based sensor web system to validate satellite-generated estimates of average soil moisture. The system was the precursor to SoilSCAPE, a system to be used to validate SMAP measurements at one or more core validation sites.

Another AIST project developed and incorporated a suite of optimization and uncertainty modeling subsystems into the NASA Land Information System (LIS)—a software framework for high-performance land surface modeling and data assimilation. Led by Christa Peters-Lidard at GSFC, this project quantified the reduction in land surface modeling uncertainty enabled by soil moisture microwave remote sensing data and demonstrated efficiency improvements to land data assimilation systems that are key to the retrieval of soil moisture profiles for the SMAP mission. Finally, Ramakrishna Nemani at NASA Ames Research Center (ARC) led a project to develop an automated anomaly detection and analysis framework for the Terrestrial Observation and Prediction System (TOPS) modeling software system. TOPS integrates numerous technologies, including satellite remote sensing, to produce "nowcasts" and forecasts that enhance decisions related to floods, droughts, forest fires, human health, and crop, range, and forest production. TOPS will integrate soil moisture data from SMAP to improve predictions of floods, droughts and crop health.

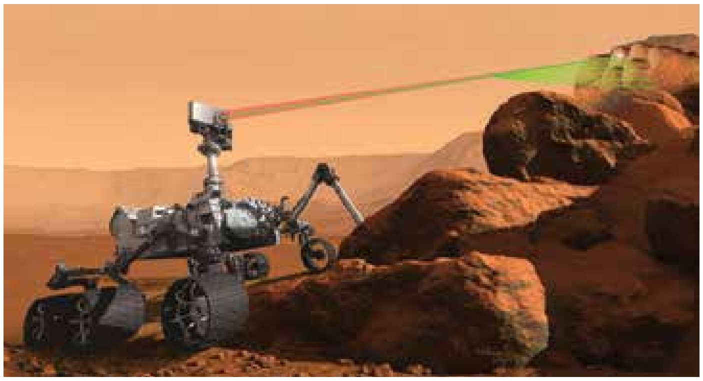
Impact: SMD's investments were critical to SMAP development, and will enable the collection of global soil moisture data. Besides being integral to our understanding of Earth's water, energy, and carbon cycles, the study of soil moisture has many applications that will benefit society, including drought monitoring, flood prediction, crop yield estimation, and weather forecasting.

Status and Future Plans: SMAP successfully launched on January 31, 2015. Its 20-ft reflector antenna was unfurled on February 24, and the mission is expected to complete initial checkout and commissioning activities by the end of April, and to begin operations in May 2015.

Sponsoring Organization: The Earth Science Division funded these technology development efforts through the AIST, IIP, and ACT programs.

Mars 2020 Instruments Will Use New Technology to Explore the Red Planet

Three SMD Technologies Selected for Mars Mission

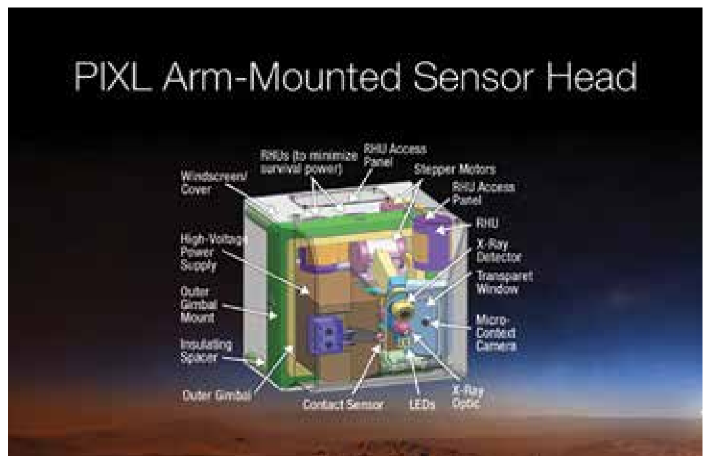


Artists' conception of NASA's Mars 2020 Rover

Infusion Project: The next NASA rover to Mars in 2020 will carry seven carefully selected instruments to conduct unprecedented science and exploration technology investigations on the Red Planet. Three of the instruments selected by the Mars Exploration Program in 2014 consist of technologies developed with funding from SMD.

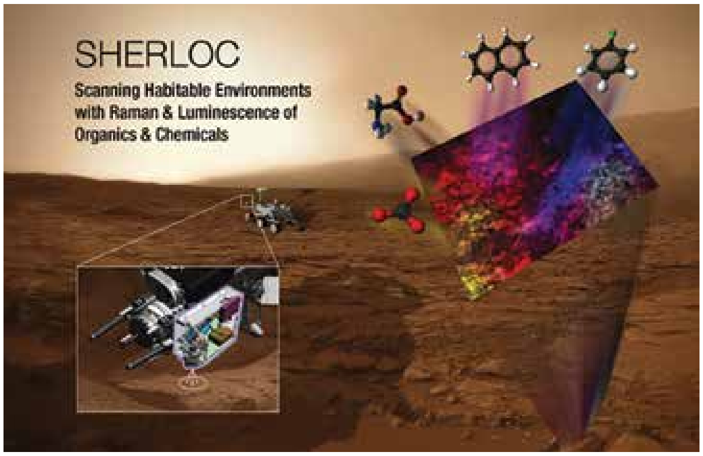
Technologies Infused: The SuperCam instrument builds upon the successful capabilities demonstrated aboard the Curiosity Rover ChemCam instrument operating on NASA's current Mars Mission. SuperCam will allow researchers to sample rocks and other targets from a distance using a laser. With support from the Planetary Science Division (PSD), Los Alamos National Laboratory developed a Laser-Induced Breakdown Spectroscopy (LIBS) technology, which can determine the elemental composition of a target from more than 20 feet away. SuperCam adds another spectrum to its laser for stand-off Raman and time-resolved fluorescence spectroscopy—a technique partially refined at Los Alamos and the University of Hawaii through a competitive award under PSD. This technology enables the molecular makeup of a target to be identified, allowing geologists to determine mineralogy and search for organic materials. SuperCam will add color to its high-resolution visible imaging capability, as well as visible and infrared spectroscopy. The PI for SuperCam is Roger Wiens from Los Alamos National Lab.

PIXL, the Planetary Instrument for X-Ray Lithochemistry, will be mounted at the end of the rover's robotic arm so that it can be placed next to a rock or soil target. PIXL is designed to provide finer-scale identification of elemental composition than previously possible on Mars. To identify elements. PIXL aims X-rays at its target, and then reads the distinctive X-rays emitted by various types of atoms when they are excited by the X-rays coming from the instrument. PIXL's design also incorporates a high-resolution camera so that the map of elemental composition can be analyzed in conjunction with visible characteristics of the target area. PIXL will be fast. It is intended to spend a few seconds to two minutes with its instrument's X-ray focused on each spot to be analyzed, then move the beam to another spot, working in a linear or grid pattern to produce a detailed map of the elements in the rock or soil target. The mapped area will be up to about the size of a postage stamp. The PI for the PIXL instrument is Abigail Allwood at the Jet Propulsion Laboratory.



Planetary Instrument for X-Ray Lithochemistry (PIXL)

SHERLOC (Scanning Habitable Environments with Raman & Luminescence for Organics and Chemicals) is an ultraviolet-light instrument that will be installed on the rover's robotic arm. SHERLOC will shine a tiny dot of ultraviolet laser light at a target causing two different spectral phenomena, which the instrument captures for analysis. The first is a distinctive fluorescence, or glow, from molecules that contain rings of carbon atoms. Such molecules may be clues to whether evidence of past life has been preserved. The second is an effect called Raman scattering, which can identify certain minerals, including those formed from evaporation of salty water, and organic compounds. This dual capability enables powerful analysis of many different compounds located in the identical spot. Developed by PI, Luther Beagle, from the Jet Propulsion Laboratory, SHERLOC has infused at least 13 technologies that were developed with support from PSD technology development programs or STMD's Small Business Innovation Research (SBIR) program.



SHERLOC will analyze the composition of rocks on the Mars surface and help determine samples to bring back to Earth for further analysis.

Impact: As part of the suite of instruments on the Mars 2020 mission, SuperCam, PIXL, and SHERLOC will enable the mission to accomplish its goals. SuperCam's updates make it the perfect instrument to provide fine-scale mineralogy, chemistry, organic detection, and color images on Mars, with the added bonus of being able to dust off a surface via laser blasts. PIXL's new X-ray focusing optic technology will allow vast improvements in the spatial resolution and acquisition time of Mars elemental composition measurements, leading to more confident and detailed interpretations of rock chemistry—a major leap forward in scientific capability that will help NASA's Mars 2020 rover mission seek evidence for past life on Mars. Not only will SHERLOC enable the search for signs of past life on Mars and selection of rock samples for possible return to Earth, it will be the first ultraviolet Raman spectrometer to fly to the surface of Mars.

Status and Future Plans: The SuperCam, PIXL and SHERLOC instruments are currently under development in anticipation of a launch in 2020.

Sponsoring Organization: These technologies were developed under the Planetary Science Division's Planetary Instrument Definition and Development Program (PIDDP), Astrobiology Science & Technology for Exploring Planets Program (ASTEP), and Astrobiology Science & Technology Instrument Development Program (ASTID). These three programs, which were established in the 1990s, served as the Planetary Science Division's technology development programs until 2013, when the division restructured its technology development efforts under the PICASSO and MatISSE programs.

2014 Discovery Announcement of Opportunity Enables Technology Infusion

NASA Offers Incentives to Use Eight New Technologies

Infusion Project: Seeking to demonstrate new technologies to enhance capabilities for the exploration of the solar system, the Planetary Science Division offered and incentivized a number of new technologies in the Discovery 2014 Announcement of Opportunity (AO). In preparation for the release of the AO, the program held a Discovery AO Technology Workshop in spring 2014. Technologists presented a wide-range of NASA-developed technologies to the scientific and engineering community. Interested parties were also able to meet one-on-one with technology representatives to address specific questions regarding proposal and implementation of the technologies on a potential Discovery mission. Based upon the interests expressed at the workshop and feedback on the draft AO, the Discovery Program determined the technologies to offer and incentivize in the final AO, which was released in early November 2014.

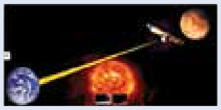
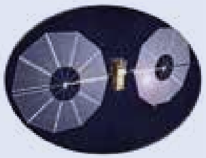
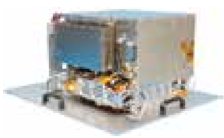
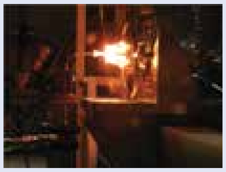
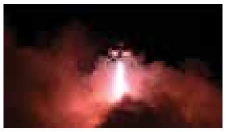
Technologies Infused: The table on the next page describes the technology infusion approaches included in the 2014 AO. All technologies offered were developed with funding from the STMD, except the NEXT-C project (funded by SMD) and ALHAT (funded by the HEOMD Advanced Exploration Systems Program).

Impact: This 2014 AO was the first effort to actively apply technologies funded by STMD in planetary missions. SMD and STMD successfully coordinated to identify technology investments in the STMD portfolio that could benefit Discovery missions. Discounting the risks associated with certain technologies helped mitigate a key impediment to the acceptance of new technologies on missions selected through a competitive peer-review process. The effort to incentivize new technologies via the Discovery 2014 AO is considered highly successful; almost every technology that was incentivized was proposed in one or more of the Discovery proposals received in early 2015. A number of the Discovery proposals evaluated the use of Green Propellant and the Deep Space Atomic Clock (DSAC), but the results of the trade studies did not support the use of these technologies. On the other hand, the Advanced Solar Array technology seems to be enabling for outer solar system missions once thought to require a radioisotope power system.

Status and Future Plans: This process to incentivize use of new technologies via AO is being matured as a model for future technology-to-flight efforts. The Discovery AO Technology Workshop was widely attended and the feedback from both the technologists and the scientific and engineering community encouraged continuation of this model to promote communication, education, and incentivization. It is anticipated that such NASA Technology Workshops will be held on a regular basis, with the next one in late 2015 or early 2016 to support the planned release of the next New Frontiers AO in late 2016.

Sponsoring Organization: The Planetary Science Division coordinated with STMD to prepare this AO.

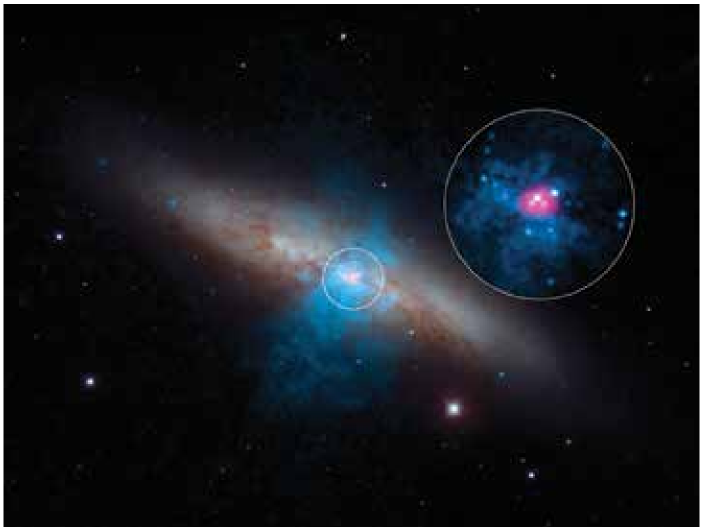
TECHNOLOGY INFUSION APPROACHES INCLUDED IN THE DISCOVERY 2014 AO

	NASA Evolutionary Xenon Thruster Commercial (NEXT-C)	The next generation solar electric ion propulsion engine that will be used to propel NASA spacecraft to investigate asteroids, comets, and the outer planets and their moons. Technology development will be transitioned to a viable commercial provider to serve multiple customers, such that NASA mission projects have easy, affordable access to the capability in the future.
	Heatshield for Extreme Entry Environment Technology (HEEET)	A woven Thermal Protection System (TPS) technology to enable in situ robotic planetary science missions such as Venus probes and landers, Saturn and Uranus probes, and highspeed sample return missions. HEEET reduces entry loads and heatshield mass for extreme entry environments.
	Deep Space Optical Communications (DSOC)	Optical communications technology to provide missions beyond the cis-lunar with 10 to 100 times increased data return over present radio frequency (RF) systems with similar spacecraft mass and power. Enabling technologies include a low-mass spacecraft disturbance isolation assembly, a flight-qualified photon counting detector array, a high-efficiency flight laser amplifier and a high-efficiency photon counting detector array for the ground-based receiver.
	Light Weight Radioisotope Heater Units (LWRHU)	Lightweight devices that use the decay of plutonium-238 to provide heat to keep spacecraft components and systems warm so that the equipment can survive long enough in the cold space environment to complete its mission.
	Advanced Solar Arrays (ASA)	Solar power technology to propel robotic and crewed missions well beyond low-Earth orbit using less propellant and weighing less than a comparable, conventional propulsion system. May enable cost-effective new trips to Mars and to asteroids across the inner solar system.
	Deep Space Atomic Clock (DSAC)	A miniaturized atomic clock that has been ruggedized for spaceflight. It will improve the precision of deep-space navigation, enable more efficient use of tracking networks, and — looking forward — serve as a key component to onboard deep-space navigation with radios.
	Green Propellant	A high-performance, high-efficiency alternative to conventional chemical propulsion systems that will enable the fuel loading of next-generation launch vehicles and spacecraft to be safer, greener, faster, and much less costly. Uses the low-toxicity Hydroxyl Ammonium Nitrate fuel/oxidizer blend (AF-M315E) developed by the U.S. Air Force as a green alternative to the hydrazine used in conventional propulsion systems.
	Autonomous Landing and Hazard Avoidance Technology (ALHAT)	Technology that enables planetary landers to automatically recognize their desired landing site, assess any and all potential landing hazards and adjust accordingly as they descend to the surface. Enabling technologies include surface-tracking sensors to precisely measure spacecraft altitude and velocity and the topography or roughness of the landing area, and high-speed, high-volume processors that use ALHAT algorithms along with the sensor data to autonomously navigate the spacecraft to a safe landing area close to the intended target.

NuSTAR Discovers Rare and Mighty Pulsar
SMD-funded Detector Technology Enables Mission Success

Infusion Project: NuSTAR—an advanced telescope designed to allow astronomers to study the universe by observing high-energy X-rays—began its two-year mission on June 13, 2012. The NuSTAR instrument consists of two co-aligned grazing-incidence telescopes with specially coated optics and hybrid detectors that extend sensitivity to higher energies, compared to previous missions such as Chandra and the X-ray Multi-Mirror Mission (XMM).

Technology Infused: Similar to the digital detectors used in cell-phone cameras, NuSTAR's detectors are made of a crystalline material (cadmium zinc telluride) divided into pixels, which absorb X-rays and create electronic signals. SMD's Astrophysics Division funded the design, development, and testing of this detector technology. The effort involved the collaboration of multiple institutions, including NASA, Caltech, Columbia University, the Danish Technical University and the Lawrence Livermore National Laboratory in Livermore, California.



NuSTAR spotted a pulsing of X-rays streaming from the ultraluminous X-ray source M82 X-2 (magenta), discovering the brightest pulsar found to date. This image combines data from three telescopes: visible light from National Optical Astronomy Observatory's 2.1-meter telescope at Kitt Peak, AZ (starlight is white, lanes of dust appear brown), low-energy X-ray data from NASA's Chandra X-ray Observatory (blue), and higher-energy X-ray data from NuSTAR (pink). (Image credit: NASA/JPL-Caltech/SAO/NOAO)

Impact: Enabled by the detector technology, NuSTAR provides a combination of sensitivity and spatial and spectral resolution improved by factors of 10 to 100 over previous missions that operated at such X-ray energies. A number of science goals drove the two-year primary mission, including the quest to develop a census of collapsed stars and black holes surrounding the center of our Milky Way Galaxy. Some key 2014 highlights of the mission include the creation of the first map of radioactive material in a supernova remnant and the discovery of the brightest pulsar ever recorded; furthermore, NuSTAR was able to capture the rare blurring of black hole light and explicitly measure the spin rate of a black hole with a mass 2 million times that of the sun.

Status and Future Plans: On July 31, 2014, NuSTAR successfully completed its primary mission, and the observatory is currently operating in its extended mission phase. NASA plans to continue NuSTAR operations up to 2016, during which time it will continue observing black holes, supernovae, and other targets, including targets of opportunity, and integrated observations with other observatories.

Sponsoring Organization: The Astrophysics Division funded the design, development, and testing of this detector technology through the APRA Program.

SYSTEMS AND SUBSYSTEMS

Innovative Antenna Mast Will Facilitate Oceanographic and Hydrologic Science "Firsts"

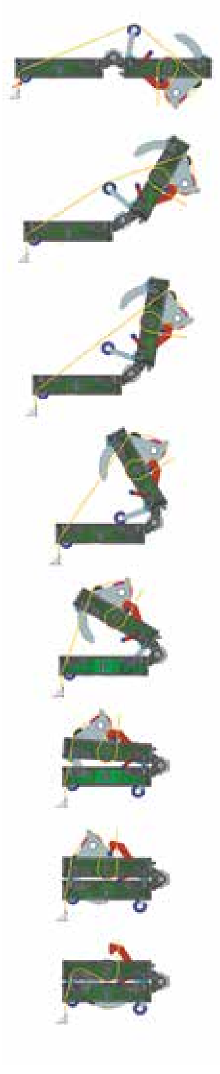
NASA Successfully Transfers New Technology to SWOT Project

Artist's concept of SWOT. (Image credit: NASA/JPL

Infusion Project: NASA is implementing the Surface Water and Ocean Topography (SWOT) mission—a tier-2 mission recommended in the 2007 NRC decadal survey—in partnership with France and Canada. The mission will enable both oceanographic and hydrologic science by providing critical information about Earth's oceans and terrestrial water bodies. The SWOT mission concept calls for a dual-antenna Ka-band radar interferometer instrument—known as KaRIn—that will map the height of water globally along two 50 km wide swaths. The KaRIn antennas, which will be separated by 10 meters on either side of the SWOT spacecraft, need to be precisely deployable to meet demanding pointing requirements.

Technology Infused: To meet the mission requirements, the SWOT antenna boom must be three times lighter and two orders of magnitude more precise than previous state-of-the-art deployable booms. In July 2013 NASA selected a baseline antenna mast design for SWOT, designed to reduce the performance margin and cost of the mission. In 2014, the ESTO-funded technology project to develop the specialized radar antenna mast completed important testing that demonstrated its capabilities and readiness to be transferred to a flight project. The project involved building a full-scale deployable prototype mast, including a multi-joint cable-driven precision latch mechanism and a lightweight pointing adjustment mechanism.

Impact: This antenna mast technology will enable SWOT to provide the first global determination of the ocean's circulation at high resolution and the first global inventory of fresh water storage, including measurements to determine temporal changes in freshwater body storage and river discharge.



Operation of the mid-boom hinge. (Image credit: G. Agnes, JPL/Caltech)

Status and Future Plans: The two-year task to design and prototype the lightweight, precision-deployable masts for KaRIn was completed in 2014. Test results indicated the design meets the deployed frequency and stability requirements for SWOT, including demonstration of deployment repeatability of +/- 2.5 arcsecs—well within the SWOT requirements of +/- 7.5 arcsecs. NASA transferred this technology to the SWOT project in late 2014 for further refinement and eventual implementation on the SWOT spacecraft, scheduled for launch in 2020.

Sponsoring Organization: The Earth Science Division provided PI Greg Agnes of the NASA Jet Propulsion Lab with funding for the SWOT antenna boom technology development project via the ACT program.

Balloon Flights Demonstrate New Astrophysics Technologies

Advanced Gamma-ray and X-ray Instruments Conduct Successful Campaigns

Infusion Projects: Through its APRA program, SMD's Astrophysics Division supports suborbital science investigations that often involve a significant level of technology development. SMD sponsored several successful balloon campaigns via APRA in 2014, including the Gamma-RAy Polarimeter Experiment (GRAPE) and the X-Calibur mission.

Technologies Infused: GRAPE applied a new type of detector technology to study celestial gamma rays—a scintillator-based Compton polarimeter optimized for wide-field polarization measurements of transient outbursts from energetic astrophysical objects. Designed and built at the Space Science Center within the University of New Hampshire's Institute for the Study of Earth, Oceans, and Space, the GRAPE payload is launched on long-duration, high-altitude balloon flights to collect data from phenomena such as gamma-ray bursts and solar flares.

X-Calibur is a low-Z Compton-scattering polarimeter designed, built, and tested by the astrophysics research group at Washington University. X-Calibur measures the polarization properties of X-rays, and when it is eventually flown in space, it could be used in a novel approach to study the most extreme objects in the universe, such as black holes, neutron stars, relativistic plasma jet formation zones, etc.

In September 2014, GRAPE studied gamma rays emitted from the Crab Pulsar, which lies in the center of the Crab Nebula. This image of the Crab Nebula combines optical survey data with X-ray data from the orbiting Chandra Observatory.

Impact: Both GRAPE and X-Calibur involve technologies that promise to advance astrophysics research. The development of new, medium-energy, gamma-ray instrumentation for GRAPE has provided a tool to improve the understanding of cosmic particle acceleration, an omnipresent and significant, yet little-understood process that occurs throughout the universe. This technology will also enable groundbreaking gamma-ray measurements of bright relativistic particle accelerators, such as galactic black holes, pulsars, and solar flares. The X-Calibur investigation involves technology that will greatly extend the capability for high-resolution X-ray spectroscopy, allowing scientists to explore what happens to space, time, and matter in the immediate vicinity of a black hole.

Status and Future Plans: On its second flight in September 2014, GRAPE successfully detected gamma rays emitted from the Crab Pulsar—the remains of a supernova explosion 6,500 light years from Earth, first observed in 1054 A.D. The 18 hour, 51 minute flight at altitudes up to 130,000 ft. allowed scientists two hours of observation of the Crab Nebula, and 16 hours of additional float time before termination. X-Calibur launched in September 2014, conducting a successful test of the instrument and a pointing system on a 7 hour, 40 minute flight at an altitude of about 126,000 ft.

Sponsoring Organization: The Astrophysics Division's APRA program sponsored both GRAPE and X-Calibur.

High-flying Spectrograph Enables Unique Astronomical Data Collection Capability

EXES Achieves Success on its First Flights

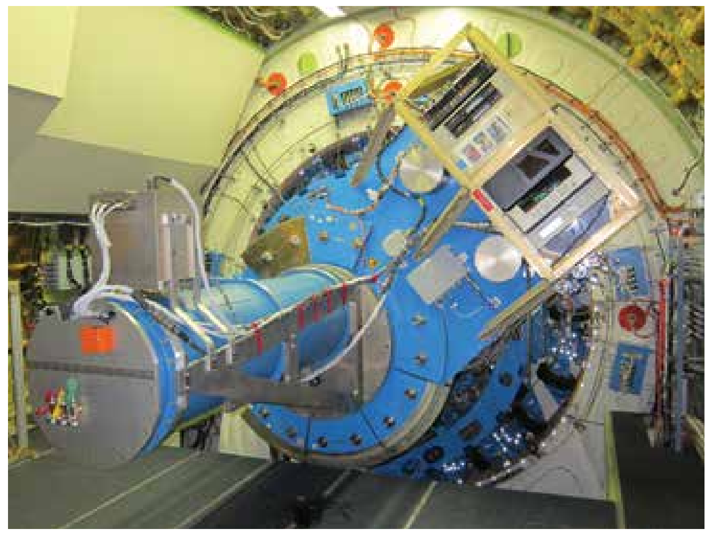
Infusion Project: The Echelon-Cross-Echelle Spectrograph (EXES) is a Principal-Investigator-class, high-resolution, mid-infrared spectrograph mounted on NASA's Stratospheric Observatory for Infrared Astronomy (SOFIA)—the world's largest flying telescope. EXES was developed by the Physics Department of the University of California, Davis in collaboration with NASA ARC in Moffett Field.

SOFIA air-to-air over the Sierra Nevada (Image credit: NASA/Jim Ross)

Technology Infused: The EXES instrument can separate wavelengths of light to a precision of one part in 100,000. At the core of EXES is an approximately 3-foot (1 meter) bar of aluminum called an echelon grating, carefully equipped to act as 130 separate mirrors that split light from the telescope into an infrared "rainbow."

Impact: EXES' high spectral resolution and SOFIA's access to infrared radiation from space will enable scientists to collect astronomical data that cannot be obtained by any other observatory, on the ground or in space. In particular, EXES' high spectral resolution enables the study of molecular hydrogen, water vapor, and methane from sources such as molecular clouds, protoplanetary disks, interstellar shocks, circumstellar shells, and planetary atmospheres.

Status and Future Plans: EXES carried out its first two flights on SOFIA on the nights of April 7 and 9, 2014. During the first commissioning flight, it observed emissions from Jupiter's atmosphere in two molecular hydrogen lines, aiding in the understanding of how gas rises from Jupiter's gloomy interior to mix with its turbulent surface. During the second flight, EXES observed a young, massive star in the constellation Cygnus that is still embedded in its natal cocoon. These first flights were considered a complete success, and the spectrograph is well on its way to becoming fully operational. EXES is among the instruments available onboard SOFIA for the observatory's Cycle 3 science observations that began in March 2015 and will extend for approximately 10 months. NASA has accepted eight EXES proposals for Cycle 3, awarding a total of 36.4 hours of observing time with EXES.



EXES mounted onboard SOFIA (Image credit: NASA/SOFIA/EXES/Mathew Richter)

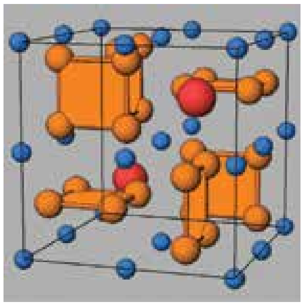
Sponsoring Organization: The Astrophysics Division sponsored this technology through the SOFIA program.

ROCKETS, POWER, AND PROPULSION

Enhanced Radioisotope Thermoelectric Generator Will Provide Missions with Increased Power

Skutterudite-based Thermoelectric Technology Ready for Transfer to Industry

Infusion Project: The Planetary Science Division's RPS Program has begun investing in the transfer of skutterudite-based thermoelectric couple technology to industry for maturation and potential integration into an enhanced Multi Mission Radioisotope Thermoelectric Generator (eMMRTG). The 2014 Nuclear Power Assessment Study (NPAS) indicated that development of RPS—including the thermoelectric converters to support these systems—is necessary to support the Planetary Science missions recommended in the NRC Decadal Survey (for more about the NPAS, see page 12). Thermoelectric power sources have consistently demonstrated their extraordinary reliability and longevity for deep space and planetary missions (RPS have supported 27 missions to date, with more than 30 years of demonstrated life) as well as terrestrial applications where unattended operation in remote locations is required.



Left: Skutterudite crystal structure. Right: naturally occurring (Fe,Co,Ni)As3 ore found in the Skutterud mine in Norway. (Image Credit: Thierry Caillat/NASA JPL)

Technology Infused: In the early 1990s, an SMD-funded study led by the Jet Propulsion Laboratory (JPL) identified the skutterudite (SKD) crystal structure as a promising thermoelectric material for use in next-generation space power systems. SMD funded subsequent work at JPL to optimize the thermoelectric properties of the skutterudite antimonide compositions, demonstrating the improved performance of skutterudites over heritage thermoelectric materials and identifying key performance degradation mechanisms. With additional SMD support, JPL continued SKD technology development by focusing on unsegmented skutterudite couple technology advancement with a view towards system integration.

Impact: Incorporation of the SKD technology into an eMMRTG system will provide 25% more power at the beginning of life, when the radioisotope thermoelectric generator is fueled, and over 50% more power at the end of design life, 17 years after fueling, compared to the MMRTG system currently used by the Curiosity rover on the surface of Mars.

Status and Future Plans: In 2014, NASA initiated the Radioisotope Power System Program (RPSP) Skutterudite Technology Maturation (STM) task by transferring the JPL-developed Skutterudite technology to Teledyne Energy Systems Inc. for the development and manufacturing and performance demonstration of SKD materials, couples, and modules. The STM task is positioned to use the current MMRTG "system platform" to transition the more efficient SKD thermoelectric technology to flight. Once the transfer of technology has been successfully completed and sufficiently matured, NASA and the DOE will determine whether to invest in the development of an eMMRTG. Currently this task is on track to advance the SKD technology to TRL 6 by end of FY18.

Sponsoring Organization: The Planetary Science Division is funding this development effort via the RPSP.

APPENDIX A. THE SMD TECHNOLOGY DEVELOPMENT STRATEGY

Each SMD science division invests in technology development programs that complement, support, and enable the implementation of the division's strategic science plan. The SMD Chief Technologist works with the SMD senior leadership team to coordinate the development and utilization of technology across the entire directorate. 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[1]. SMD's approach is to mature required technologies years in advance of flight mission implementation, thereby retiring risk, reducing cost, and increasing the likelihood that new technologies will be incorporated into flight projects.

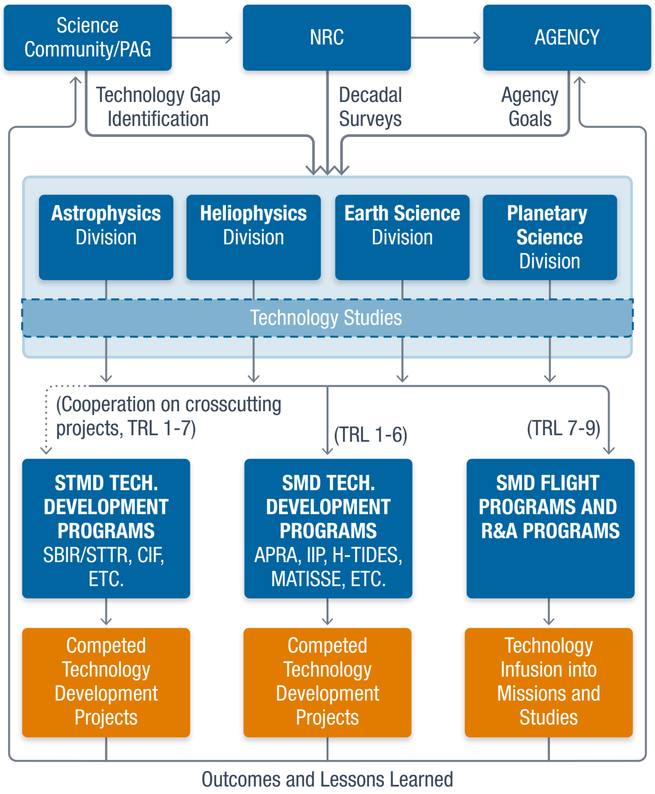
Along with other organizations outside of SMD, the Space Technology Mission Directorate (STMD) is an important SMD partner in this process, particularly for technology development efforts that are applicable Agency-wide. SMD consults and collaborates with STMD to identify new opportunities, develop specific solicitations, co-fund technology developments, and review and evaluate ongoing developments with a view toward technology infusion. 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 near- to mid-term mission needs. The SMD Chief Technologist is 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.

Effective technology development requires careful analysis of technology gaps, identification of technologies to fill those gaps, and sustained investment to advance the chosen technologies. SMD executes most of its internal technology development through its divisions using the general process depicted on the next page. SMD applies this robust process to mature technologies to an advanced technology readiness level[2] (TRL) such that they can be applied in a flight mission or scientific research and analysis project. Most internal SMD technology development efforts are related to science observations (instrument development) or information (data validation, processing). SMD also accomplishes technology development by establishing partnerships with other government agencies, higher education institutions, and industry. In addition, SMD funds student fellowship programs such as the Nancy Grace Roman Technology Fellowship and NASA Earth and Space Science Fellowship (NESSF) and leverages technology development

1 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).

2 See https://www.nasa.gov/content/technology-readiness-level/ for a definition of NASA TRLs.

efforts sponsored through NASA center research and development funds.



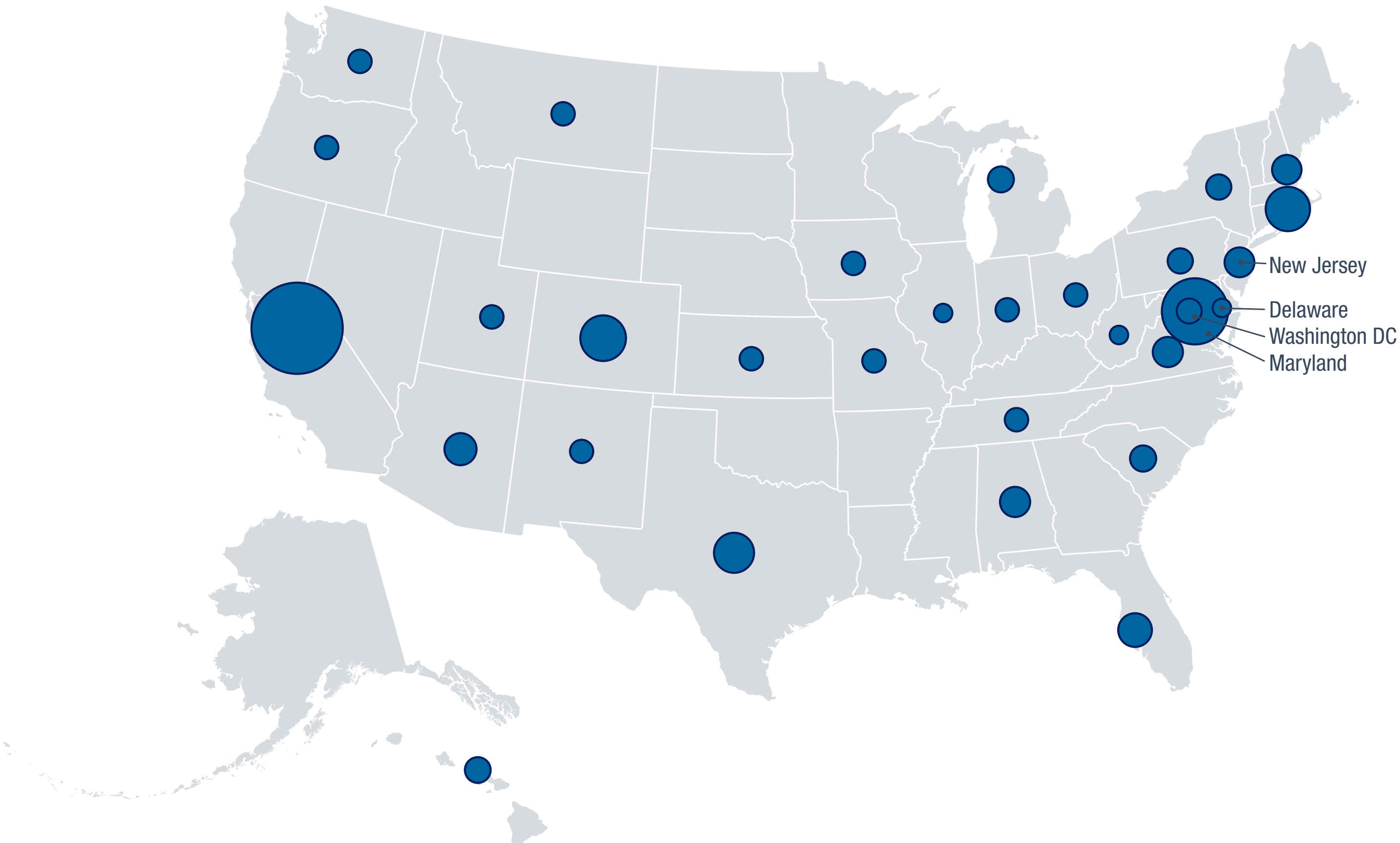
General SMD technology development process.

Note that the SMD technology development process is cyclical, with information on SMD technology development efforts provided to the organizations that, in turn, advise SMD. SMD divisions receive guidance from the NRC Decadal Surveys and the science community and direction from the Agency. The divisions carefully consider this input and determine the technology development efforts to invest in, based on the science requirements. Each division accomplishes its internal technology development via competed opportunities offered through technology development programs (typically for technologies at TRLs 1-6) or via directed or competed flight programs (typically for technologies at TRLs 7-9). Many technology development efforts are guided by studies. SMD divisions establish their own technology development programs to actively manage internal technology development efforts that are implemented outside of flight programs, thus ensuring progress and value are achieved for the directorate's investments. (See the table on page 06 for a list of SMD technology development programs.) Divisions organize their technology development programs to align with their specific needs; e.g., some divisions organize technology development programs according to the type of technology (instruments, observations, etc.) and some according to TRL (low, medium).

SMD sponsors various types of competed opportunities; some request ideas for development, others are in response to a specific set of division requirements. However, all competed technology development opportunities within SMD employ a peer review process to determine the optimal investment strategies. 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.

The science community and the Agency receive regular feedback regarding the progress of technology development efforts so they can influence SMD technology investments effectively.



Distribution of PI institutions for SMD technology development efforts active in 2014; the size of the circle corresponds to the number of technology development efforts led by PIs in the state.

This report highlights a sample of the activities comprising the broad portfolio of SMD technology projects. In 2014, SMD division technology development programs funded numerous projects distributed throughout the nation (see map above). Principal Investigators (PIs) leading SMD technology development projects reside at various U.S. institutions.

ACRONYMS	
ACT	Advanced Component Technologies
ADD	Agile Digital Detector
AFTA	Astrophysics Focused Telescope Assets
AIST	Advanced Information Systems Technology
ALHAT	Autonomous Landing and Hazard Avoidance Technology
AO	Announcement of Opportunity
APRA	Astrophysics Research and Analysis
ARC	Ames Research Center
ASA	Advanced Solar Arrays
CDA	Cosmic Dust Analyzer
CIF	Center Innovation Fund
DOE	Department of Energy
DSAC	Deep Space Atomic Clock
DSOC	Deep Space Optical Communications
eMMRTG	enhanced Multi Mission Radioisotope Thermoelectric Generator
ESTO	Earth Science Technology Office
EXES	Echelon-Cross-Echelle Spectrograph
FPS	Fission Power Systems
GRAPE	Gamma-Ray Polarimeter Experiment
GSFC	Goddard Space Flight center
HAMMR	High-frequency Airborne Microwave and Millimeter-wave Radiometer
HEEET	Heatshield For Extreme Entry Environment Technology
HEOMD	Human Exploration and Operations Mission Directorate
HLC	Hybrid Lyot Coronagraph
H-TIDeS	Heliophysics Technology and Instrument Development for Science
IIP	Instrument Incubator Program
JPL	Jet Propulsion Laboratory
JWST	James Webb Space Telescope
LADEE	Lunar Atmosphere and Dust Environment Explorer
LASP	Laboratory For Atmospheric and Space Physics
LDEX	Lunar Dust Experiment
LIBS	Laser-Induced Breakdown Spectroscopy
LIS	Land Information System
LWRHUS	Light Weight Radioisotope Heater Units
MatISSE	Maturation of Instruments for Solar System Exploration
MDL	Microdevices Lab
MMRTG	Multi Mission Radioisotope Thermoelectric Generator
MSFC	Marshall Space Flight Center

ACRONYMS

NDA	Nano Dust Analyzer
NESSF	NASA Earth and Space Science Fellowship
NEXT-C	NASA Evolutionary Xenon Thruster Commercial
NOAA	National Oceanic and Atmospheric Administration
NPAS	Nuclear Power Assessment Study
NRC	National Research Council
NWNH	New Worlds, New Horizons
OCE	Office of the Chief Engineer
PAG	Program Advisory Group
PI	Principal Investigator
PICASSO	Planetary Instrument Concepts for the Advancements of Solar System Observations
PIXL	Planetary Instrument for X-Ray Lithochemistry
PSD	Planetary Science Division
R&A	Research and Analysis
RF	Radio Frequency
RFI	Radio Frequency Interference
RPS	Radioisotope Power Systems
RPSP	Radioisotope Power System Program
SAT	Strategic Astrophysics Technology
SBIR	Small Business Innovation Research
SHERLOC	Scanning Habitable Environments with Raman & Luminescence for Organics and Chemicals
SKD	Skutterudite
SMAP	Soil Moisture Active Passive
SMD	Science Mission Directorate
SOFIA	Stratospheric Observatory For Infrared Astronomy
SPC	Shaped Pupil Coronagraph
STEREO	Solar Terrestrial Relations Observatory
STM	Skutterudite Technology Maturation
STMD	Space Technology Mission Directorate
STTR	Small Business Technology Transfer
SWOT	Surface Water and Ocean Topography
TCOR	Technology Development for Cosmic Origins
TDEM	Technology Development for Exo-Planet Missions
TOPS	Terrestrial Observation and Prediction System
TPCOS	Technology Development For Physics of the Cosmos
TPS	Thermal Protection System
TRL	Technology Readiness Level

ACRONYMS

UV	ultraviolet
WFIRST	Wide-Field Infrared Survey Telescope
XMM	X-Ray Multi-Mirror Mission

National Aeronautics and Space Administration

NASA Headquarters
300 E Street SW
Washington, DC 20024-3210
www.hq.nasa.gov

www.nasa.gov