During the pandemic, Goddard employees met virtually to continue developing their technologies. The Goddard employees shown on the computer monitor include (from top, left to right): Sun Hur-Diaz, Victoria Wu, Sarah Dangelo, Michael Romeo, Noble Hatten, Lauren Schlenker, Steven Hughes, Sean Semper, Andrew Liounis, and Samuel Price.
In the years to come, we’ll likely remember 2020 as the strangest of our lifetimes. We were only six months into fiscal year 2020 (FY20) when NASA shuttered its facilities due to the global pandemic, requiring employees to work from home. Although denied access to their labs on center — the lifeblood for many technologists funded by our Internal Research and Development (IRAD) and Center Innovation Fund (CIF) programs — some principal investigators received center approval to create offices and improvised labs in their homes. They re-engineered their lives.

For those able to work from home, the existing challenges and less-than-perfect conditions didn’t stop them. In many respects, FY20 proved no different than in previous years, at least in terms of results. Our return-on-investment — that is, the gains in follow-on NASA R&D funding, awarded instrument-development efforts and missions — more than compensated for our initial investment in these investment areas and exceeded our expectations.

Using Microsoft (MS) Teams meetings and other virtual collaboration tools, our innovators submitted mission and instrument proposals and advanced concepts. They submitted a record number of New Technology Reports (NTRs) and applied for patents. They forged new partnerships. They secured flight opportunities, won follow-on funding and Phase-A mission studies, and completed technologies used in simulators and other critical-support capabilities. We even succeeded in holding virtual IRAD Pre-Collaboration Workshops, Innovation Workshops, and our Annual IRAD Poster Session, giving our innovators a platform to share their work.

We didn’t miss a beat.

This isn’t to say our program wasn’t adversely affected by mandatory stay-at-home telework. However, researchers stepped up and juggled the work they could complete while also caring for loved ones, young and old. Others couldn’t complete their projects because they didn’t have access to critical laboratory equipment; however, Goddard’s Office of the Chief Technologist remained flexible. We allowed researchers to shift their focus when it made sense for them to develop more designs and carry out trades, analyses, and other IRAD-related activities. Consequently, the IRAD program has provided follow-on funding to complete these research efforts in FY21.

Even so, I’m awed by what our people managed to accomplish under difficult circumstances. They persevered. This report offers a snapshot of what our innovators achieved in 2020. To me, they are heroes.

Peter Hughes
Chief Technologist
Goddard Space Flight Center

“Don’t wait until everything is just right. It will never be perfect. There will always be challenges, obstacles, and less-than-perfect conditions. So what? Get started now....”

— Mark Victor Hansen, American Author
Goddard leadership values research and development and, thus, is committed to funding and effectively managing Goddard’s Internal Research and Development (IRAD) program and the NASA Headquarters-funded Center Innovation Fund (CIF).

Leadership knows R&D attracts, retains, and cultivates talented scientists and engineers. It creates experts in critical and advanced technologies NASA needs to fulfill its goals. This dual investment in the workforce and innovative technologies positions the center to continue winning new missions and instrument starts in areas important to NASA and Goddard’s role in Agency missions. Without IRAD and CIF funding, Goddard could not maintain its leadership in certain scientific disciplines and technical capabilities.

### FY20 Program Quick Takes

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Award of Follow-On Tech Funding:
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Instrument Incubator Program (IIP); Development and Advancement of Lunar Instrumentation (DALI); Planetary Instrument Concepts for the Advancement of Solar System Observations (PICASSO); and Heliophysics Technology and Instrument Development for Science (HTIDeS); Space Communications and Navigation (SCaN)

New Technology Reports (NTRs):
278; up from 205 in FY19 (Goddard Total)

Instrument/Mission Design Studies:
10 (IRAD-funded)

Breakdown of FY20 IRAD and CIF Awards

- Science SmallSat Technology 8%
- Planetary Science 15%
- Heliophysics 13%
- Earth Science 15%
- Astrophysics 20%
- Communication and Navigation 11%
- Cross Cutting Capabilities 16%
- Suborbital Platforms and Range Services 2%
New Technology Reports (NTRs) Provide Benchmark for Gauging Success

NTRs capture information about technical discoveries, improvements, innovations, and inventions so that NASA can disseminate these technologies appropriately under its mandated technology-transfer program. Since many of these NTRs result from IRAD- or CIF-funded efforts, they also gauge the success of our R&D programs.

By the close of FY20, Goddard technologists filed 278 reports, far exceeding the 205 submitted in 2019. Of all NASA's 11 field centers, Goddard came in second in the number of NTRs submitted.
measurements of important physical processes affecting space weather and astronaut safety.

In FY20, NASA also selected her fluxgate magnetometer as one of three Goddard-developed instruments that will make up the Heliophysics Environmental and Radiation Measurement Experiment (HERMES) to fly on NASA’s orbital outpost, Gateway. The data will help alert astronauts to severe space weather events that could jeopardize their health and safety.

In FY20, many new missions awarded to Goddard scientists and engineers originated in the Heliophysics Division, as did two of the four Phase-A/Step-1 studies. Goddard heliophysicists received follow-on funding — valued in the millions of dollars — from the Heliophysics Technology and Instrument Development for Science (HTIDes) program and were tapped to provide instruments for the agency’s orbiting lunar station, Gateway.

In a crowd of achievers, Zesta distinguished herself. A pioneer in the field of magnetometry, she dedicated herself to miniaturizing magnetometers, ubiquitously used instruments that measure magnetic fields. And because of her success, she has dramatically expanded the instruments’ use on smaller platforms, thereby enabling simultaneous, multipoint measurements of important physical processes affecting space weather and astronaut safety.

Dione, HERMES and the Future

Her latest success is a new pathfinding CubeSat mission called Dione, which she is leading. In addition to flying her fluxgate magnetometer that debuted on the Goddard-developed Dellingr mission in 2017, Dione will fly two other IRAD-developed instruments and a third provided by Utah State University and Virginia Tech. Together, they will study how Earth’s upper atmospheric layers react to the ever-changing flow of solar energy into the magnetosphere.

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— Eftyhia Zesta, Goddard Heliophysicist

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“The reason [the miniaturized fluxgate magnetometer] was selected was because of its size, which IRAD paid for,” said Steven Christe, Zesta’s colleague. “This instrument is good for everything.”

And last year, Zesta, with support from NASA’s HTIDeS program, started working with her colleagues to develop a self-calibrating fluxgate magnetometer that would correct for drift. Such an instrument would benefit spaceflight as well as in-situ instruments on Earth.

“It’s exciting to finally see the fruits of our long efforts from all these past years. We are, I believe, the poster child for our IRAD program,” Zesta said.

And the IRAD Team Award Goes to... Heliophysics Researchers

“We don’t normally recognize a collection of teams, but this year proved different in so many ways. We needed to shine a light on the incredible work these heliophysics teams have done.”

— Goddard Chief Technologist Peter Hughes

In past years, the Office of the Chief Technologist made a point of selecting researchers from across Goddard’s lines of business to receive the IRAD Innovator of the Year and Team Awards. FY20 proved an exception.

Both the IRAD Innovator of the Year [see page 5] and our special Team award went to scientists and engineers developing instruments and missions that advance our understanding of the Sun-Earth system. This decision seemed appropriate given the sheer number of CubeSat/SmallSat missions that the Heliophysics Division has won in recent months and scientists’ success in leveraging the division’s capabilities.

So instead of selecting just one team, we decided to recognize a collection of teams now developing important missions.

These missions — Dione, petitSat, GTO-Sat, and CeRES — are pathfinders. They all carry smaller, less-expensive, and more versatile instruments developed or kick-started with IRAD support. They are also being leveraged for use on many other missions — a fact that demonstrates the instruments’ value and scientists’ ability to work together to get more bang for their efforts.

Principal Investigator Shri Kanekal holds an early version of a detector that he further modified for the Miniaturized Electron pRoton Telescope (MERIT) that will fly on NASA’s Gateway.
**Dione**, for example, is carrying the miniaturized fluxgate magnetometer, developed by Innovator of the Year Eftyhia Zesta; the Ion-Neutral Mass Spectrometer (INMS), which debuted on Dellingr’s maiden flight, and the Dual Electrostatic Analyzer (DEA), which will fly on Endurance. It’s expected to launch in 2022.

The **Plasma Enhancements in the Ionosphere-Thermosphere Satellite (petiSat)**, led by Jeffrey Klenzing and Alexa Halford, is expected to launch in 2021. It also leverages INMS as well as the Dellingr spacecraft bus.

The **Geosynchronous Transfer Orbit Satellite (GTOSat)**, also slated for a 2021 launch, is being built on the Modular Architecture for a Resilient Extensible SmallSat (MARES) bus — a follow-on to Dellingr (see page 13).

The **Compact Radiation belt Explorer (CeREs)**, developed by Shri Kanekal and the Southwest Research Institute, flew a compact telescope. Although this technology, performed flawlessly in testing, the mission was lost after launch due to mechanical failures. However, it is being leveraged for use on the Miniaturized Electron pRoton Telescope (MERIT) and Gateway (see page 9).
The goal of Goddard’s IRAD and CIF programs is providing seed funding for promising, sometimes risky technologies that have the potential to bring about revolutionary ways to explore the world around us.

Our researchers typically follow a specific path to success. They flesh out their ideas with IRAD and CIF support, seek follow-on funding through other NASA funding programs, and demonstrate their technologies in a space or near-space environment aboard sounding rockets, research aircraft, high-altitude balloons, CubeSats/SmallSats, and the International Space Station.

In the end, the goal is to infuse these technologies into new missions or instrument builds that broaden our understanding of the Sun, Earth, solar system, and universe. This chapter details some of those accomplishments, and shines a spotlight on the success of an IRAD-funded instrument that has distinguished itself on the Goddard-led OSIRIS-REx mission (see below).

### Successful Mission Applications: OSIRIS-REx Meets Mission Requirements; Acquires New Insights

In October 2020, NASA’s OSIRIS-REx mission received images confirming the spacecraft had collected more than enough material to meet one of its mission requirements — acquiring at least 2 ounces, or 60 grams, of the asteroid Bennu’s surface material. Also busy on the mission was the Goddard-developed Visible and Infrared Spectrometer (OVIRS), which was developed by Dennis Reuter and Amy Simon in part with IRAD support. Not only did the mission use OVIRS’s measurements to select a sampling site, the instrument discovered that hydrated minerals, or clays, carbonates, and organics are widespread on Bennu.

(Investment Area: Planetary Science)

This image, taken in April 2020, highlights asteroid Bennu’s equatorial craters and its boulder-filled surface. Before the mission collected enough material to meet mission requirements, a Goddard instrument helped identify a sampling site.
New Missions

Hermes Gateway

When NASA issued a call for fast-turnaround instruments to fly on Gateway, Goddard heliophysicists responded and were rewarded mightily for their efforts. Of the four individual instruments that will make up a space weather instrument suite on NASA’s lunar-orbiting outpost, Gateway, Goddard will provide three, all developed with IRAD funding.

They include: 1) the Miniaturized Electron pRoton Telescope (MERIT), developed by Shri Kanekal; 2) fluxgate magnetometers, provided by FY20 IRAD Innovator of the Year Eftyhia Zesta; and 3) the Electron Electrostatic Analyzer (ESA), developed by Daniel Gershman.

Collectively known as the Heliophysics Environmental and Radiation Measurement Experiment (HERMES), the instruments will monitor radiation to gain a more complete understanding of cosmic and solar rays, and more particularly alert astronauts to potentially harmful radiation requiring that they take shelter.

(Investment Area: Heliophysics)
Dione

Eftychia Zesta, who truly distinguished herself in FY20, won a new CubeSat mission called Dione. This pathfinding spacecraft is a prototype and will carry four miniaturized instruments that will study how Earth’s upper atmosphere reacts to the ever-changing flow of solar energy into the magnetosphere. Three of those instruments — the fluxgate magnetometer, the Ion-Neutral Mass Spectrometer, and the Dual Electrostatic Analyzer, also developed by Eftychia Zesta — all received IRAD support and are slated to fly on several other missions. Dione is expected to be the most densely packed CubeSat ever flown and is expected to launch in 2022. (Investment Area: Heliophysics)

Dione will gather data not collected since NASA’s dual-spacecraft Dynamics Explorer mission launched in the early 1980s.

The Mini Ion-Neutron Mass Spectrometer, or Mini-INMS, (below) has provided some of the first direct measurements of particles in the upper atmosphere since the 1980s. It is slated to fly on several upcoming CubeSat/SmallSat missions.
“Though many developments within LunaNet were accomplished in FY20, one of the most significant successes was when NASA SCaN adopted LunaNet. This level of adoption and visibility was further emphasized by the significant mention of LunaNet in the September 2020 NASA Administrator’s publication of the revised Artemis plan.”

— Kendall Mauldin, LunaNet Principal Investigator

**Focusing Optics X-ray Solar Imager (FOXSI-4)**

For the fourth time, NASA will be flying the FOXSI payload on a Black Brant sounding rocket. Selected by NASA’s Heliophysics Flight Opportunities for Research and Technology (HFORT) program, FOXSI-4 will carry an advanced X-ray attenuator developed by Principal Investigator Kyle Gregory. FOXSI-4, which also involves Goddard scientist Steven Christe, will determine how superhot plasma arises during flares. *(Investment Area: Heliophysics)*

A Black Brant sounding rocket (below) will carry the fourth Focusing Optics X-ray Solar Imager (FOXSI) payload. This time, FOXSI will carry an advanced X-ray attenuator.

**Ground Imaging to Rocket Investigation of Auroral Fast Features (GIRAFF)**

Principal Investigator Robert Mitchell will develop two identical sounding rocket payloads — each carrying an electron spectrometer and magnetometer — to investigate electron precipitation within the fastest auroral structures known as flickers and fast-pulsating aurora. One of the instruments on the payload is based on the optics from the Dual Electrostatic Analyzer, also flying on the Dione CubeSat (see page 7). NASA’s Heliophysics Flight Opportunities for Research and Technology (HFORT) program selected Mitchell’s proposal. *(Investment Area: Heliophysics)*

**Auroral Waves Excited by Substorm Onset Magnetic Events (AWESOME)**

Goddard scientist Robert Mitchell is serving as the co-investigator of another sounding rocket mission, AWESOME. Funded by NASA’s Heliophysics Flight Opportunities for Research and Technology (HFORT) program, University of Alaska researcher Mark Conde will launch three sounding rockets to study perturbations occurring in Earth’s high-latitude thermosphere during auroral substorms. Mitchell will provide the mission’s ground-based imaging support. *(Investment Area: Heliophysics)*

Astronauts aboard the International Space Station took this photo of the Aurora Borealis on Jan. 20, 2016. Goddard is developing sounding rocket payloads to investigate these natural light shows.
Solar eruption Integral Field Spectrograph (SNIFS)

SNIFS will explore the energetics and dynamics of the Sun’s chromosphere with an ultraviolet integral field spectrograph flying on a sounding rocket. The spectrograph employs a mirrorlet array developed at Goddard, with support from the IRAD program. (Investment Area: Heliophysics)

Multi-Mission cFS using NOS3

Although SmallSats cost a fraction of traditional satellite missions, the cost and complexity of developing flight software is about the same, leading to prohibitive flight software costs. Principal Investigator Alan Cudmore aimed to maximize the reuse of flight software across multiple SmallSat missions through a technology called the NASA Operational Simulator for Small Satellites (NOS3). This software is currently being used by five SmallSat missions and future upgrades will be funded by the missions. (Investment Area: Heliophysics)

Technology Infusion and Flights

Large-Area, High-Efficiency Diffractive Optics for Solar Imaging

In 2019, the National Science Foundation selected the Virtual Super-resolution Optics with Reconfigurable Swarms (VISORS) mission, a formation-flying CubeSat mission to demonstrate high-resolution extreme ultraviolet solar imaging, particularly individual dissipation regions in the solar corona. Central to VISORS is the Goddard-developed photon sieve technology, which Goddard scientist Adrian Daw will provide, along with science support. With this technology, scientists believe they will begin to more fully understand the mechanisms powering the corona. (Investment Area: Heliophysics)

Radiation-Tolerant Multi-Input, Multi-Output Software Defined Radio (SDR)

SDR is an enabling technology for instruments and communication systems, and essential for reducing the size, weight, power, and costs for future CubeSat and SmallSat missions. In FY20, Principal Investigator Nicholas Franconi reported that he completed the architecture for a radiation-tolerant SDR, which is now being incorporated into multiple follow-on, FY21 IRADs, as well in the development of the new Modular Architecture for a Resilient Extensible SmallSat (MARES) bus (see page 13). Franconi expects to increase the SDR’s technology-readiness level from the current TRL-4 to TRL-6 this fiscal year. A demonstration aboard the International Space Station is planned for 2022. (Investment Area: Crosscutting Technologies)

Tech Infusion: LunaNet Adopted for Artemis-Era Communications and Navigation

Talk about moving fast. At the beginning of FY20, Goddard researchers were at the early stages of developing a flexible and extensible lunar communications and navigation architecture called LunaNet.

Within months, NASA’s Space Communications and Navigation (SGCN) program had baselined the architecture for NASA’s Artemis program — a development that couldn’t have happened without IRAD support. “The IRAD program investments through FY20 were exactly what was needed to take this architecture forward,” said Principal Investigator Kendall Mauldin. (Investment Area: Communications and Navigation)
Modular Architecture for Resilient Extensible SmallSat (MARES)

In FY20, a team developing Goddard’s new SmallSat platform, MARES, planned to integrate and test two critical components: the core command and data handling (C&DH) unit and the high-performance SpaceCube 3.0 mini processor. Due to the pandemic, Principal Investigator Robin Ripley couldn’t complete the testing, but reported that MARES’s C&DH is baselined for GTOSat (see page 7) and a Dali-funded technology for lunar studies. In addition, MARES is being considered for a mission proposal and the SpaceCube 3.0 mini is being funded as a stand-alone box on Coronal Discharge Experiment (CODEX), an experiment on STP-H9-SCENIC, and Lunar Gateway.
(Investment Area: Science SmallSat Technology)

Cryogenic Etching of Ultra-Low Reflective Black-Silicon for NIR, Mid-IR and Submillimeter Wavelengths

Led by scientist Ron Shiri, a team is investigating patterned, etched black silicon for use in next-generation pupil masks, important components in internal coronagraphs that block bright starlight to create a dark zone revealing the relatively faint planets in orbit around their host stars. Etched black silicon, like carbon-nanotube coatings, help absorb straylight, thereby enhancing a coronagraph’s ability to block bright light. In FY20, Shiri and his team delivered a one-inch black silicon mask and three sets of carbon-nanotube coated metallic wafers for testing aboard the International Space Station. (Investment Area: Astrophysics)

(Left) More than a work of art, the etched black silicon masks are designed to absorb straylight in coronagraphs.
Phase-A/Step-1 Studies

NASA’s Small Explorer and Mission of Opportunity Selections

In FY20, Goddard astrophysicists and engineers fared well in NASA’s recent selection of potential Explorer-class missions, participating in three of the four teams chosen to flesh out their concepts with Phase-A funding. From these proposals, NASA is expected to choose one full Small Explorer (SMEX) mission and one or two Missions of Opportunity by the end of 2021.

Dorado, led by Goddard scientist Brad Cenko, is a mission of opportunity expected to fill a critical gap in the emerging field of multi-messenger astrophysics. Cenko is collaborating with Principal Investigator Javier Del Hoyo, who received FY20 IRAD funding to optimize the fabrication of ultraviolet multilayer coatings for the mission’s refractive telescope.

The other contender is the LargE Area burst Polarimeter (LEAP), led by the University of New Hampshire. Goddard scientists John Krizmanic and Steve Stur-ner are lending their modeling expertise to this mission aimed at studying the energetic jets launched when massive stars die.

And Goddard astrophysicist Terri Brandt, in a strategic partnership with the University of California-Berkeley, is providing a thermal control system for the Compton Spectrometer and Imager (COSI), which is competing as a SMEX mission. It would scan the Milky Way to measure gamma rays from radioactive elements produced during stellar explosions.

These drawings show a proposed CubeSat mission called Dorado. Led by Goddard scientist Brad Cenko, Dorado, if chosen, would fill a critical gap in the emerging field of multi-messenger astrophysics.
Heliophysics Flight Opportunities for Research and Technology (HFORT) Studies

In addition to selecting a handful of sounding rocket missions in FY20, the HFORT program also awarded Step-1 funding to a couple Goddard-proposed efforts. Principal Investigator Alex Glocer received support for Storm Time O+ Ring current Imaging Evolution (STORIE), which would answer questions about the origin and energization of near-Earth plasma from the International Space Station.

And Co-Investigators Nick Paschalidis and Sarah Jones received funding to advance the Instrument for Studying Exospheric Neutral Density (ISEND), led by the University of Alaska. ISEND is envisioned as a 12U SmallSat that would carry the miniaturized Ion-Neutral Mass Spectrometer, which is being used on a variety of other missions (see page 7). This mission would measure neutral densities along a highly elliptical geostationary-transfer orbit, and traces its heritage to GTOSat and Delling.

(Investment Area: Heliophysics)

Flight Opportunities

In-Space Manufacturing Technique

Goddard engineer Vivek Dwivedi believes telescopes in the future won’t be built and assembled on Earth, but in space. However, NASA will need to advance in-space manufacturing techniques before this can become a reality. In FY20, NASA’s Space Technology Mission Directorate selected Dwivedi to demonstrate a coating technology called atomic layer deposition (ALD) — one of many steps in building large telescopes in space. ALD has never been demonstrated in space. Dwivedi will be flying a football-sized ALD chamber aboard a Blue Origins New Shepard launch vehicle during the second quarter of 2021 to demonstrate that a thin layer can be deposited on a sample.

(Investment Area: Crosscutting Capabilities)
Gigabit Ethernet Data Recorder

The Sounding Rocket Program Office at the Wallops Flight Facility has long wanted a high-speed data recorder that would collect science data at rates faster than the downlink rate. A team led by Principal Investigator Chris Lewis has developed such a device, called Galois. It is expected to be demonstrated on SubTec-9 in the spring of 2022. (Investment Area: Suborbital Platforms and Launch Services)

Development and Flight Test of Modernized Electronics for Mesosphere/Lower Thermosphere Fields Payload

Principal Investigator Rob Pfaff successfully completed the design of electronic boxes and circuits for a completely updated and modernized “Goddard sphere,” a legacy instrument that measures weak electric fields in the mid-latitude ionosphere. Pfaff expects to demonstrate the instrument on two sounding rocket missions in 2021. Based on the technology demonstration’s results, Pfaff plans to use the instrument in future sounding rocket science missions. (Investment Area: Heliophysics)

Development of Miniature GPS Package for Deployable Sub-Payloads

In FY20, Principal Investigator Joshua Yacobucci aimed to develop a miniature GPS package for deployable subpayloads, which are ideal for gathering in-situ observations on sounding rocket flights. The technology could replace the inertial navigation systems that rely on a magnetometer to determine the payload’s position, orientation, and velocity. Since these measurements are based on previous positions, errors are cumulative and grow over time. Yacobucci has developed the system, which will be demonstrated on the Sporadic E Electrodynamics (SEED) experiment in mid-2021 aboard the U.S. Bariatya sounding rocket mission. It also is slated for other missions. (Investment Area: Suborbital Platforms and Range Services)
Follow-On Funding to Advance Technology-Readiness

The IRAD and CIF programs are not meant or able to provide cradle-to-grave support. Therefore, a key success metric is whether principal investigators succeed in securing follow-on funding to advance their technologies. In FY20, several NASA R&D programs and divisions awarded Goddard technologists the funding they needed to further advance their technologies. (See page 3 for list of funding sources.)

Goddard Earth Scientists Score Multiple Instrument Incubator Program (IIP) Awards

FY20 proved fruitful for Goddard’s Earth Science Division, whose researchers garnered six IIP awards, valued at $11.7 million. They cover everything from advanced lidars for measuring formaldehyde to new antennas. A short synopsis of each is below.

(Investment Area: Earth Science)

• Global L-Band Active/Passive Observatory for Water Cycle Studies (GLOWS): Under this $4.3 million award, Co-Investigator Rajat Bindlish is helping to advance a smaller, lower-cost large-aperture antenna for a future L-Band mission offering Soil Moisture Active Passive (SMAP)-like measurements.

• Formaldehyde Integrated Path Differential Absorption Lidar: IIP awarded Principal Investigator Thomas Hanisco $990,000 to advance a core technology, supported by the IRAD program, which would specifically measure formaldehyde, a difficult-to-measure chemical important in climate studies.

• Breakthrough Technologies Enabling ESPA-Class SmallSat Implementation of Earth Science Lidar Missions: Principal Investigator Mark Stephen received $800,000 to reduce the cost, size, and power requirements of remote-sensing lidar systems. In addition to incorporating photonic integrated circuits, Stephen is advancing photonic crystal fiber gas cells, more efficient optical amplifiers, and a new telescope with custom free-form optics.

• Metasurfaces for Compact, Next-Generation Polarimetric Remote Sensing of Aerosols and Clouds: Goddard Co-Investigator Kerry Meyer, who has teamed with Harvard University, is defining science applications and measurement requirements for a cloud-and-aerosol instrument camera. IIP awarded the team $311,000 in funding.

•Compact Hyperspectral Air Pollution Sensor-Demonstrator (CHAPS-D): Co-Investigator Scott Janz is working with the Applied Physics Lab to demonstrate a hyperspectral imager, equipped with free-form optics. He received $390,000 to support this work. CHAPS-D could be flown on a SmallSat or as a hosted payload to measure pollution sources.

$4.3 million for large-aperture antenna

$990,000 for formaldehyde instrument

$800,000 for lidar system

$390,000 for hyperspectral imager

$311,000 for science applications

$4.9 million for innovative SmallSat concept
Setting the Stage for a New Way to Monitor Earth

In FY20, IIP awarded $4.9 million to the developers of a first-of-its-kind SmallSat concept that would employ a lidar, a miniaturized spectrometer, and artificial intelligence to strategically monitor changes on Earth.

Led by Principal Investigator Guangning Yang, the Concurrent Artificially Intelligent Spectrometry and Adaptive Lidar Systems (CASALS) would use a space-based lidar system to create 3D images that would help monitor for the first time from one tiny satellite the heights of forests, ice (on land and sea), and clouds and aerosols. Equipped with machine-learning algorithms, CASALS would identify when the spacecraft is over a forest or ice sheet and autonomously adjust its lidar to obtain relevant, detailed information.

(Investment Area: Earth Science)

SUBsurface Lunar Investigation and Monitoring Experiment (SUBLIME)

NASA has not measured moonquakes since Apollo astronauts deployed a handful of measuring stations at various locations on the lunar surface. But that will change under NASA’s Artemis program if Goddard Principal Investigator Terry Hurford has his way. With $3.5 million in DALI funding, he is advancing a next-generation, highly rugged seismometer, called SUBLIME, that would monitor seismic activity and map the Moon’s interior, from its regolith to its core. The system, easily deployed by astronauts, would also alert astronauts to moonquakes, which are common on the Moon.

(Investment Area: Planetary Science)
Small Lidar for Profiling Water Vapor and Winds from Planetary Landers

NASA’s PICASSO program awarded a Goddard team $900,000 to advance a Mars lidar system that leverages technology originally created to measure carbon levels in Earth’s atmosphere. With the funding, the team is building RAmen-Mass Spectrometer (RAMS)

With his $1.3 million in PICASSO funding, Principal Investigator Andrej Grubisic is demonstrating a TRL-4 RAMS hybrid breadboard instrument that could acquire micron-level composition maps of organic molecules and mineral phases that exist in samples gathered on comets and asteroids as well as from samples acquired on the icy moons in the outer solar system. (Investment Area: Planetary Science)

Development of a COmpact Rapid Electron (CORE) Instrument

A team, led by Principal Investigator Daniel Gershman, received more than $650,000 in HTIDeS funding to develop the CORE instrument, which would be able to provide highly sensitive measurements of electrons in the solar wind. Gershman believes CORE would be faster at collecting particle data than a similar-type instrument on NASA’s Magnetospheric Multiscale mission — but it would carry out its mission aboard a CubeSat. (Investment Area: Heliophysics)

RAmen-Mass Spectrometer (RAMS)

This artist’s rendition shows how a Mars lidar could be deployed on a landed mission to Mars.

This is a closeup of the lidar instrument, which would remotely profile, for the first time, water vapor up to nine miles above the Martian surface, along with wind speeds and minute particles suspended in the planet’s atmosphere.

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GPS Receivers on the Moon

A satellite-based navigation system used by four billion people worldwide is being eyed as a solution for piloting in and around the lunar orbit.

In FY20, NASA’s Space Communications and Navigation (SCaN) program awarded Principal Investigator Munther Hassouneh about $1 million to raise the technology-readiness level of the NavCube 3.0 mini GPS receiver to TRL 6, which means it could be used for future lunar missions. Instead of building new infrastructure around the Moon, Hassouneh wants to extend Earth-based GPS technology to the Moon.

With his SCaN funding, Hassouneh and his team will be advancing a stand-alone, multi-frequency GPS receiver based on the Goddard-developed, high-altitude Navigator GPS technology originally developed for NASA’s Magnetospheric Multiscale (MMS) mission. The new receiver incorporates Goddard’s SpaceCube-3 mini processor and an IRAD-developed application-specific integrated circuit (ASIC) reduces the receiver’s size and weight.

(Investment Area: Communications and Navigation)

Ultra-Low Noise Bolometric Detectors for Mid- to Far-Infrared Space Observatories

Under his FY20 IRAD, Principal Investigator Ari Brown designed a microfabrication strategy for bolometric detector arrays — a technology identified as a potential capability for the Origins Space Telescope (OST), one of the proposed astrophysics 2020 Decadal large strategic mission concepts. (Investment Area: Astrophysics)

Attitude-Control System Testing Facility

In FY16, Principal Investigator Zach Peterson began work on a testbed that would help CubeSat mission developers test attitude control systems (ACS) — a capability that could make the difference in avoiding on-orbit mishaps. In FY20, Peterson reported that the Coronal Discharge Experiment (CODEX) mission and Goddard’s SmallSat ACS group have both expressed interest in this capability and have offered to help fund the technology.

(Investment Area: Science SmallSat Technology)

Capturing an X-ray Pulsar Navigation and Pulsar Science Payload

Two years ago, a Goddard team demonstrated X-ray navigation (XNAV) aboard the International Space Station. In FY20, the team secured funding from another government agency to explore the use of XNAV for resilient timing networks, which involves developing a high-fidelity simulation to explore and evaluate the performance of XNAV for low-Earth orbit, geostationary orbit, and lunar regimes. In the meantime, the team is working to develop an XNAV payload for Gateway and provide XNAV simulation hardware and software to the Johnson Space Center.

(Investment Area: Communications and Navigation)
Critical Support Capabilities

Goddard-developed technologies do not always find berths on spacecraft or instruments. In some cases, their sole purpose is assisting scientists in the interpretation of data or providing NASA with capabilities needed to fly missions.

Fuzzing Flight Software

Principal Investigator Jose Martinez Pedrazza successfully implemented an automated “fuzz testing” technique to Goddard’s widely used core Flight System (cFS). The testing technique, which can be scaled for minutes, hours, or days, automatically bombards cFS systems with pseudo-random and unexpected inputs to find situations where software purposely crashes. The cFS project could further improve this technology, and other software projects may now apply the technique to their own software products, Pedrazza said. (Investment Area: Crosscutting Technologies)

Enabling Rapid, End-to-End, Medium-Fidelity Optimization of New Classes of Planetary Science Missions

Principal Investigator Noble Hatten wanted to improve Goddard’s ability to design atmospheric entry trajectories and missions to the moons of the gas giants. The goal was to expand the capabilities of Goddard’s Evolutionary Mission Trajectory Generator (EMTG). According to Hatten, the team exceeded its expectations, and Goddard’s ability to rapidly design trajectories for both atmospheric entry and moon missions is now vastly improved. The enhanced EMTG is now supporting several mission proposals. (Investment Area: Planetary Science)

Design Reference Architecture for Imaging Instruments

Principal Investigator Terry Smith established a Design Reference Architecture that will help reduce the development time for imaging instruments. Now ready for use, the architecture extended Goddard’s capability in the field of Model-Based System Engineering. (Investment Area: Crosscutting Capabilities)

In House: Low-Cost, Low-Noise, High-Voltage Pulsar-Driver for Spaceborne Electro-Optics

Future lidar systems used by scientists across Goddard’s scientific disciplines — Earth science, heliophysics, and planetary science — would all benefit from a flight Q-switch driver for use on SmallSats. In FY20, a team led by Principal Investigator Amandeep Kaur, advanced the Q-switch technology, which Goddard’s Planetary Environments Laboratory is demonstrating to perform high-resolution mass spectroscopy. (Investment Area: Planetary Science)
Patent Applications and Commercialization

Other important success metrics are the filing of patent applications for technologies developed with IRAD support as well as efforts to commercialize new capabilities.

**Advanced X-ray Attenuator**
Advances in X-ray spectroscopic imaging detectors promise a greater understanding of the energy release and particle acceleration that power solar eruptions. However, X-ray detectors can become saturated. Principal Investigator Kyle Gregory is developing an attenuation filter that overcomes the flux problem. Gregory submitted a patent application for his technology and plans to fly it on the FOXSI-4 sounding rocket (see page 11).
*(Investment Area: Heliophysics)*

**CMOS Plasma Spectrometer Follow-On Prototype Instrument**
Led by Principal Investigator Adam Schoenwald, a team set out to develop a spectrometer capable of measuring plasma density in the mesosphere. Despite the shutdown, the team continued characterizing its proof-of-concept instrument and plans to eventually fly the instrument on a sounding rocket. Also, in FY20, the group completed a patent application for the technology.
*(Investment Area: Earth Science)*

**Miniaturation of Power System Electronics Housekeeping Functions**
Principal Investigator George Suarez, who is developing the Radiation-Hardened Power System Electronics Housekeeping ASIC for power-system electronics, reported in FY20 that Apogee Semiconductor and Vorago Technologies are interested in possibly commercializing the technology once Suarez completes the design. In addition, Suarez has received a patent for the technology.
*(Investment Area: Crosscutting Capabilities)*

**Impulse Control System (ICS)**
ICS is a high-impulse, low-thrust electric propulsion system for SmallSat attitude and orbit control, constellation formation, and low-thrust maneuvers. In FY20, Principal Investigator Robert Moss submitted a patent application for the technology, which is manifested on the petitSat mission, scheduled for a May 2021 launch (see page 7).
*(Investment Area: Science SmallSat Technology)*

**Profile in Excellence: Twelfth Mission and Counting**
Scientists and engineers can spend their entire careers developing technologies, and maybe, if they’re lucky, fly them on a handful of missions. Goddard scientist and innovator Nick Paschalidis must be an extraordinarily lucky man. With the launch of the European Space Agency’s Solar Orbiter in February 2020, Paschalidis contributed mission-enabling instruments, instrument subsystems, and spacecraft avionics to 12 high-profile missions—a number that doesn’t include the three CubeSat missions for which he contributed instruments. And that number is still climbing, with additional missions in the development pipeline.
*(Investment Area: Heliophysics)*

*In FY20, Goddard scientist Nick Paschalidis achieved what few do: with the launch of the Solar Orbiter in February, he contributed instruments and other gear to 12 high-profile space missions.*
R&D is a high-risk endeavor. In some cases, the research does not yield the expected outcome or result. In others, the principal investigator achieves precisely what he or she set out to accomplish. Here we spotlight just a few early-stage, often higher-risk technologies across Goddard’s lines of business that could result in the center creating new opportunities and helping NASA carry out its science and exploration missions.

EarthShine: Our World as an Exoplanet, from the Surface of the Moon

Principal Investigator Padi Boyd asked a simple question: how will scientists know they’ve found a habitable planet when they see it? Do they have a proxy dataset to make the call? Her answer: why not view Earth as an exoplanet.

While Earth is the best-studied habitable planet, efforts to collect a dataset of Earth as an exoplanet proxy, and then compare that data to sophisticated atmospheric models, are sparse.

With her FY20 IRAD, Boyd examined how NASA might deploy a lunar-based instrument suite to gather continuous observations of Earth. This data, Boyd believes, could help determine whether naturally occurring changes in seasons, cloud cover, oceans and continents can be disentangled from those variations due to life. Work is continuing.

(Investment Area: Astrophysics)

On August 23, 1966, NASA’s Lunar Orbiter 1 snapped the first photo of Earth as seen from lunar orbit. A Goddard scientist wants to use the lunar orbit to study Earth as an exoplanet proxy.
**Sun-Earth**

**Spontaneous IRAD (SPIRAD): Formation-Flying Sunshade**

Principal Investigator Doug Rabin is designing a meter-class sunshade deployable from a CubeSat or SmallSat. Such a device could greatly increase the signal-to-noise ratio of ultra-high angular resolution observations of the solar corona. After surveying existing concepts for meter-class occulters, Rabin’s team discovered nothing met the requirements for simplicity and scalability; however, the team didn’t give up. Fortunately, team member Anne-Marie Novo-Gradac drew inspiration from decorative fans, a possible design the team is now pursuing. Work is continuing.

*(Investment Area: Heliophysics)*

**The Universe**

**Photonics Chip Laser Metrology System for LUVOIR**

Principal Investigator Kenji Numata, working with an industrial partner, completed the design of an integrated photonics circuit (PIC) that would help align multi-segmented telescopes envisioned for the proposed Large Ultraviolet/Optical/Infrared Surveyor, or LUVOIR mission. The goal is to produce a PIC metrology system with picometer-level accuracy. Numata said work is continuing under an FY21 IRAD.

*(Investment Area: Astrophysics)*

**Balloon-Borne Cryogenic Telescope Testbed (BOBCAT)**

Principal Investigator Al Kogut developed an ultra-lightweight dewar for cooling far-infrared telescope components — a technology he believes could enable Great Observatory-type science aboard scientific balloons. In FY19, Kogut demonstrated he could transfer liquid helium and had planned to further demonstrate his concept in FY20; however, the pandemic shutdown halted that effort. Work is continuing, as Kogut works with NASA’s Small Business Innovation Research (SBIR) program to commercialize the ultra-light technology.

*(Investment Area: Astrophysics)*

**The Life-Finding Detector**

Principal Investigator Jack Sadleir reported significant results in his quest to develop a radiation-hardened detector capable of directly identifying biosignatures on exoplanets — a goal of three conceptual, next-generation astrophysics missions. He and his team achieved record-setting detector sensitivity, more than what is required for these proposed Decadal missions.

*(Investment Area: Astrophysics)*

**The Moon and Beyond**

**Agile Radiometer for Regolith Observations using microWaves (ARROW)**

In FY20, Principal Investigator David Hollibaugh Baker planned to mature a lunar passive microwave radiometer to a technology-readiness level of four. The pandemic hindered him from assembling the instrument, but he reported progress for his astronaut-deployed package that would help characterize the physical properties, including the presence of water ice, of the upper 10 meters of lunar regolith. Work is continuing.

*(Investment Area: Planetary Science)*

**Machine Learning 3D Lunar Data Analysis**

When NASA returns to the Moon, intelligent machines will play a big role in the exploration. Principal Investigator Matthew Brandt is helping to pave the way for these smart systems. In his FY20 IRAD, Brandt developed a program capable of autonomously analyzing lunar terrain data and detecting hazards. Although work is continuing, Brandt reported that the neural networks he created are teaching algorithms to quickly identify craters and other drastic slopes.

*(Investment Area: Planetary Science)*

**Toward Scientific Autonomy: Applying Machine Learning to MOMA Science Data**

Another IRAD Principal Investigator James MacKinnon is working with a mass spectrometer similar to the Mars Organic Molecule Analyzer (MOMA), which is one of several instruments aboard Endurance, a rover mission. MacKinnon specifically wants to teach rovers through machine learning how to independently choose which targets to analyze. In contrast, MOMA requires human intervention. According to MacKinnon, the team is making good progress.

*(Investment Area: Planetary Science)*

www.nasa.gov/gsftech
Application of Charge Mitigating Thin Film Technology for Lunar Exploration

Principal Investigator Vivek Dwivedi and his partners developed a coating that, if used on spacesuits and other gear, could help prevent lunar dust from adhering to virtually everything it touches. The coating, made of indium tin oxide, is currently being tested on samples flying on the International Space Station. In FY20, Dwivedi scaled up the process for coating larger samples, using a novel particulate rotary reactor. (Investment Area: Planetary Science)

Below: A team of Goddard technologists are experimenting with coated pigments to solve one of NASA’s biggest challenges: how to keep the Moon’s irregularly shaped dust grains from adhering to virtually everything they touch. In FY20, the Goddard team developing the technology scaled up the process for coating from 5 grams to 25 grams, using a novel particulate rotary reactor.

Astronaut-Carried Magnetometers for the Moon and Beyond

With his FY20 IRAD, Principal Investigator Jared Espley began developing and testing a concept for an astronaut-carried magnetometer that could be used on the Moon. Espley has identified NASA’s Artemis III program as the technology’s first customer. (Investment Area: Planetary Science)

Multidisciplinary Applications

Computed Tomography in Space

A group of Goddard engineers is advancing a non-invasive diagnostic tool that astronauts could use to evaluate the structural integrity of tools and other space gear they make in space. Principal Investigator Justin Jones and his team are developing a microwave oven-sized Computed Tomography, or CT, scanner capable of detecting flaws in 3D-printed flight hardware at micron scales and identifying metals in geological samples that could be used to make tools and other devices. The team is planning to apply for NASA R&D funding to further develop the technology. (Investment Area: Crosscutting Technology)
Planet Earth

Time-varying Optical Measurements of Clouds and Aerosol Transport (TOMCAT)

As wildfires raged across the western states in the fall, Goddard scientists became more convinced that their smaller, more versatile lidar system for monitoring clouds and aerosols was a much-needed capability for next-generation space missions. TOMCAT, which weighs less than 200 pounds and measures just 35 inches in length, width, and depth, the instrument is ready for a flight opportunity. (Investment Area: Earth Science)

Below: The TOMCAT mission, shown here in this artist’s drawing, provides a low-cost, high-TRL solution for essential cloud and air-quality profiling needs. Inset: Litespar, Inc., developed the TOMCAT laser, which is qualified and packaged for SmallSat use.
**Aerovator: An Advanced Kite-Borne Instrumentation System**

Scientists use high-altitude balloons, sounding rockets, and research aircraft to collect remote-sensing data. Principal Investigator Geoff Bland wants to add kites to the mix. In FY20, Bland began advancing methods for lofting miniature instruments with kites. The idea is that these small instruments could capture fine-scale data important to both Earth science and planetary missions. Work is continuing. (Investment Area: Earth Science)

**Suborbital Flights and Range Services**

**Wallops Mesonet Prototype**

Principal Investigator Philip Smith has made significant progress establishing a prototype meso-network of weather stations, which will help monitor regional weather patterns on the Delmarva Peninsula — weather data important to Wallops launch services. In FY20, Smith and his team installed sensor stations, identified a system to disseminate data to range meteorologists and Earth scientists, and identified stakeholders. The goal is developing a 25-node network once fully built. (Investment Area: Suborbital Platforms and Range Services)

**Navigating and Communicating**

**Direct RF Digitization Receiver for Multi-GNSS, Communications, and More**

The use of multiple Global Navigation Satellite Systems will be critical in the future. Principal Investigator Lonnie Labonte started developing a next-generation front-end GPS receiver that will, in principal, digitize the entire L-band and allow the frequency band to be selected through firmware. It would be programmable on flight. The new approach will allow a flexible and modular capability. Work will continue under an FY21 IRAD. (Investment Area: Communications and Navigation)

**Autonomous Navigation, Guidance, and Control (autoNGC) System**

Increased onboard autonomy won’t completely cut ground controllers out of the equation, but Principal Investigator Sun Hur-Diaz believes self-driving navigation, guidance, and control (NGC) systems will save time and precious resources particularly for CubeSats operating near Earth, around the Moon, and near small bodies. Hur-Diaz is working on NGC software that would autonomously support a wide range of spacecraft. Key to her efforts is a plug-and-play architecture compatible with Goddard’s core Flight System (cFS) framework. (Investment Area: Communications and Navigation)

Below: Working from her home office, Principal Investigator Sun Hur-Diaz evaluates the autoNGC architecture for use in and around the Moon.

Photo Credit: Ruben Diaz