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Cutting edge
Goddard's Emerging Technologies

The Just-Right Orbit

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Chad Mendelsohn, Trevor Williams, and Don Dichmann, with TESS orbit in background
(Photo Credit: Pat Izzo/NASA)

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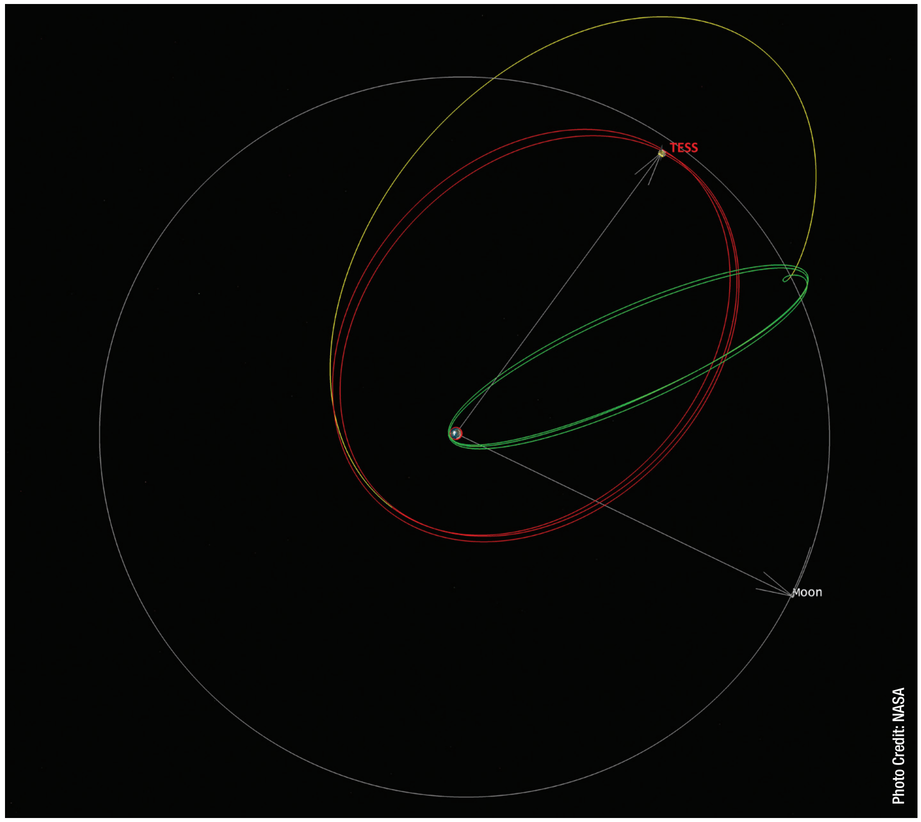
The Just-Right Orbit

Winning Team Selects Never-Before-Used Orbit for Planet Finding

Principal Investigator George Ricker likes to call it the "Goldilocks orbit" — it's not too close to Earth and her Moon, and it's not too far. In fact, it's just right.

And as a result of this never-before-used orbit — advanced and fine-tuned by Goddard engineers and other members of the Transiting Exoplanet Survey Satellite (TESS) team — the Explorer mission led by Ricker will be perfectly positioned to map the locations of more than 500 transiting exoplanets, extrasolar planets that periodically eclipse each one's host star. When the two-year mission begins in 2017, it will represent the first time NASA has examined a large number of small planets around the brightest and closest stars in the sky.



This image shows the Transiting Exoplanet Survey Satellite's trajectory from launch to final mission orbit. The green line represents the phasing loops before the lunar flyby. The yellow is the resulting trajectory from the flyby and the red shows the final mission orbit.

Previous sky surveys with ground-based telescopes have mainly detected giant planets, while NASA's Kepler observatory has uncovered the existence of many smaller exoplanets, but their host stars are faint and difficult to study.

TESS, which NASA recently selected as its next Explorer mission along with the Goddard-developed Neutron Star Interior Composition Explorer (*CuttingEdge*, Spring 2013, Page 2), will use an array of wide-field cameras to perform the all-sky survey of a broad range of exoplanets, ranging from Earth-size to gas giants.

From this survey data, the James Webb Space Telescope and large ground-based observatories will be able to further characterize the targets, making it possible for the first time to study the masses, sizes, densities, orbits, and atmospheres of a large cohort of small planets, including a sample of rocky worlds in the habitable zones of their host stars.

"TESS will carry out the first spaceborne all-sky transit survey, covering 400 times as much sky as any previous mission," said TESS Principal Investigator Ricker, a senior research scientist at the Massachusetts Institute of Technology's (MIT) Kavli Institute for Astrophysics and Space Research. "It will identify thousands of new planets in the solar neighborhood, with a special focus on planets comparable in size to the Earth."

Ricker's winning team also includes Goddard, which is managing the mission; MIT's Lincoln Laboratory; Orbital Sciences Corporation (OSC); NASA's Ames Research Center; the Harvard-Smithsonian Center for Astrophysics; The Aerospace Corporation; and the Space Telescope Science Institute.

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"This is a great mission and it stands on its own merits," added Tim Sauerwein, who managed the TESS proposal effort at Goddard. "I certainly don't attribute the win solely to the orbital analyses performed by our team, but I strongly believe they contributed. This orbit is absolutely ideal for this mission."

Special Orbit Required

To carry out an exhaustive two-year survey of extrasolar planets in both celestial hemispheres, TESS needed to occupy a very particular position in space, a highly stable place that maximized sky coverage and gave the observatory a mostly unobstructed view of the cosmos, all from a low-radiation, thermally benign environment.

After exhaustive studies by Goddard engineers and The Aerospace Corporation, the TESS team chose a never-before-used lunar-resonant orbit known as P/2 in the parlance of scientists. This high-Earth, highly elliptical orbit has a period half that of the Moon's orbital period, meaning that the satellite makes a complete orbital circuit every 13.7 days.

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Traveling to Hard-to-Reach Destinations Made Easier

Technologist Develops Fully Automated Tool for Calculating Trajectories

Traveling to remote locations sometimes involves navigating through stop-and-go traffic, traversing long stretches of highway, and maneuvering sharp turns and steep hills. The same can be said for guiding spacecraft to far-flung destinations in space.

It isn't always a straight shot.

A Goddard technologist has developed a fully automated tool that gives mission planners a preliminary set of detailed directions for efficiently steering a spacecraft to hard-to-reach interplanetary destinations, such as Mercury, Jupiter, Saturn, and most comets and asteroids.

The tool, the Evolutionary Mission Trajectory Generator (EMTG), "offers a paradigm shift from what we normally do," said Jacob Englander, the Goddard technologist who devised a concept for his computer-based tool while a doctorate student at the University of Illinois. "EMTG will be used, and already is being used, to develop trajectories for proposed Goddard missions that cannot be designed using any other current tool."

Science Unto Itself

Determining mission configurations, which EMTG accomplishes on a standard desktop computer, is a science unto itself.

Early interplanetary missions were confined to Earth's immediate neighbors: first Venus, then Mars. The total change in velocity, which on Earth is akin to stepping on the gas to propel your vehicle even faster, was low enough that direct flights were possible using 1960s chemical-based thruster technology. Travel to more distant destinations, however, required a larger change in velocity, and therefore more propellant — not always possible with mass-constrained spacecraft.

A way to overcome that obstacle was executing a planetary flyby, a slingshot-type maneuver where a spacecraft uses the relative movement and gravity of a planet or other celestial body to alter its path and speed. First proposed in 1961, NASA has used this technique in interplanetary missions since Mariner 10 in 1964.

But determining the number and locations of planetary flybys to gain gravitational assists is easier said than done — a process requiring the computation of complex mathematical equations calculated by powerful computers.

What makes Englander's technology unique, he said, is the fact that mission developers needn't first make an educated guess as they currently do of a possible spacecraft trajectory or path to a particular target. Unlike other trajectory-design tools, "ours is fully autonomous," explained Englander, who used Center Innovation Fund support to create the EMTG's algorithms and software.

No Noodling Required

Without any forethought or noodling, all mission developers need to do with his tool is input a series

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Hagopian Achieves Another Milestone in Emerging Nanotechnology

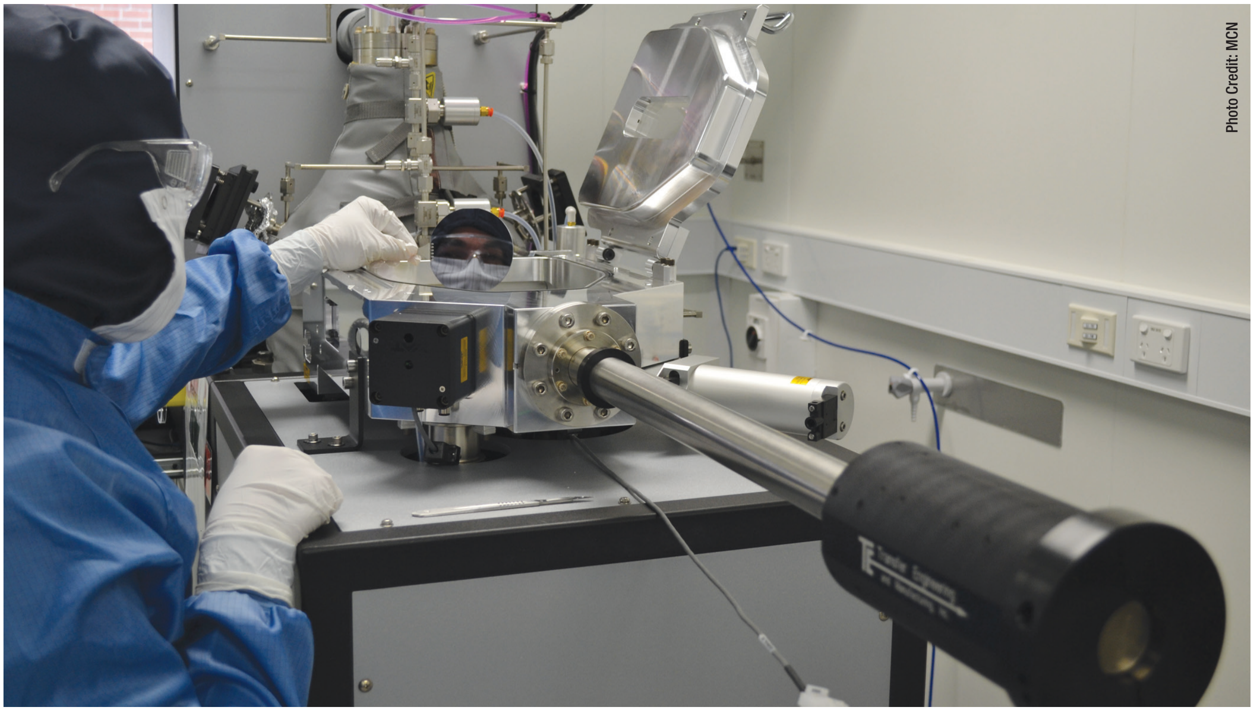

Photo Credit: MCN

Lachlan Hyde, an expert in atomic layer deposition (ALD) at Australia's Melbourne Centre for Nanofabrication, is working with one of the organization's two ALD systems.

Goddard optics engineer John Hagopian, a recent winner of a NASA technology award, has achieved yet another milestone in his quest to advance an emerging super-black nanotechnology that promises to make spacecraft instruments more sensitive without enlarging their size.

Hagopian and his team have demonstrated that they can grow a uniform layer of carbon nanotubes through the use of another emerging technology called atomic layer deposition (ALD) (*CuttingEdge*, Summer 2012, Page 6). The marriage of the two technologies now means that NASA can grow nanotubes on three-dimensional components, such as complex baffles and tubes commonly used in optical instruments.

"The significance of this is that we have new tools that can make NASA instruments more sensitive without making our telescopes bigger and bigger," said Hagopian, who recently won NASA's "Honor Award for Exceptional Technology Achievement" due to his pioneering work applying carbon-nanotube technology to spaceflight needs. "This demonstrates the power of nanoscale technology, which is particularly applicable to a new class of less-expensive tiny satellites called Cubesats that NASA is developing to reduce the cost of space missions."

Since beginning his research and development effort five years ago, Hagopian and his team have made significant strides applying the carbon-nanotube technology to a number of spaceflight applications, including, among other things, the suppression of stray light that can overwhelm faint signals that sensitive detectors are supposed to retrieve.

During the research, Hagopian tuned the nano-based super-black material to make it ideal for this application. Testing has shown that the material absorbs on average more than 99 percent of the ultraviolet, visible, infrared, and far-infrared that strikes it — a never-before-achieved milestone that now promises to open new frontiers in scientific discovery (*CuttingEdge,* Winter 2012, Page 6). The material consists of a thin coating of multi-walled carbon nanotubes about 10,000 times thinner than a strand of human hair.

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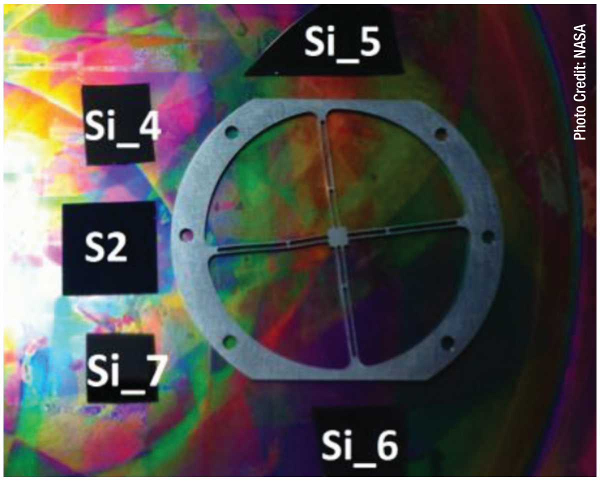

Australia's Melbourne Centre for Nanofabrication applied a catalyst layer using atomic layer deposition to this occulter mask.

Once a laboratory novelty grown only on silicon, the NASA team now grows these forests of vertical carbon tubes on commonly used spacecraft materials, such as titanium, copper, and stainless steel. Tiny gaps between the tubes collect and trap light, while the carbon absorbs the photons, preventing them from reflecting off surfaces. Because only a small fraction of light reflects off the coating, the human eye and sensitive detectors see the material as black.

Before growing this forest of nanotubes on instrument parts, however, materials scientists must first deposit a highly uniform foundation or catalyst layer of iron oxide that supports the nanotube growth. For ALD, technicians do this by placing a component or some other substrate material inside a reactor chamber and sequentially pulsing different types of gases to create an ultra-thin film whose layers are literally no thicker than a single atom. Once applied, scientists then are ready to actually grow the carbon nanotubes. They place the component in another oven and heat the part to about 1,832 degrees Fahrenheit (750 degrees Celsius). While it heats, the component is bathed in carbon-containing feedstock gas.

"The samples we've grown to date are flat in shape," Hagopian explained. "But given the complex shapes of some instrument components, we wanted to find a way to grow carbon nanotubes on three-dimensional parts, like tubes and baffles. The tough part is laying down a uniform catalyst layer. That's why we looked to atomic layer deposition instead of other techniques, which only can apply coverage in the same way you would spray something with paint from a fixed angle."

ALD to the Rescue

ALD, first described in the 1980s and later adopted by the semiconductor industry, is one of many techniques for applying thin films. However, ALD offers an advantage over competing techniques. Technicians can accurately control the thickness and composition of the deposited films, even deep inside pores and cavities. This gives ALD the unique ability to coat in and around three-dimensional objects.

Hagopian's colleague, Goddard technologist Vivek Dwivedi, is now advancing ALD reactor technology customized for spaceflight applications through a partnership with the University of Maryland-College Park.

To determine the viability of using ALD to create the catalyst layer while Dwivedi was building his new ALD reactor, Hagopian engaged through the Science Exchange the services of the Melbourne Centre for Nanofabrication (MCN), Australia's largest nanofabrication research center. The Science Exchange is an online community marketplace where scientific service providers can offer their services. The NASA team delivered a number of components, including an intricately shaped occulter sample to be used in a new NASA-developed instrument for observing planets around other stars.

Through this collaboration, the Australian team fine-tuned the recipe for laying down the catalyst layer — in other words, the precise instructions detailing the type of precursor gas, the reactor temperature, and pressure needed to deposit a uniform foundation. "The iron films that we deposited initially were not as uniform as other coatings we have worked with, so we needed a methodical development process to achieve the outcomes that NASA needed for the next step," said Lachlan Hyde, MCN's expert in ALD.

The Australian team succeeded, Hagopian said. "We have successfully grown carbon nanotubes on the samples we provided to MCN and they demonstrate properties very similar to those we've grown using other techniques for applying the catalyst layer. This has really opened up the possibilities for us. Our goal of ultimately applying a carbon-nanotube coating to complex instrument parts is nearly realized." ❖

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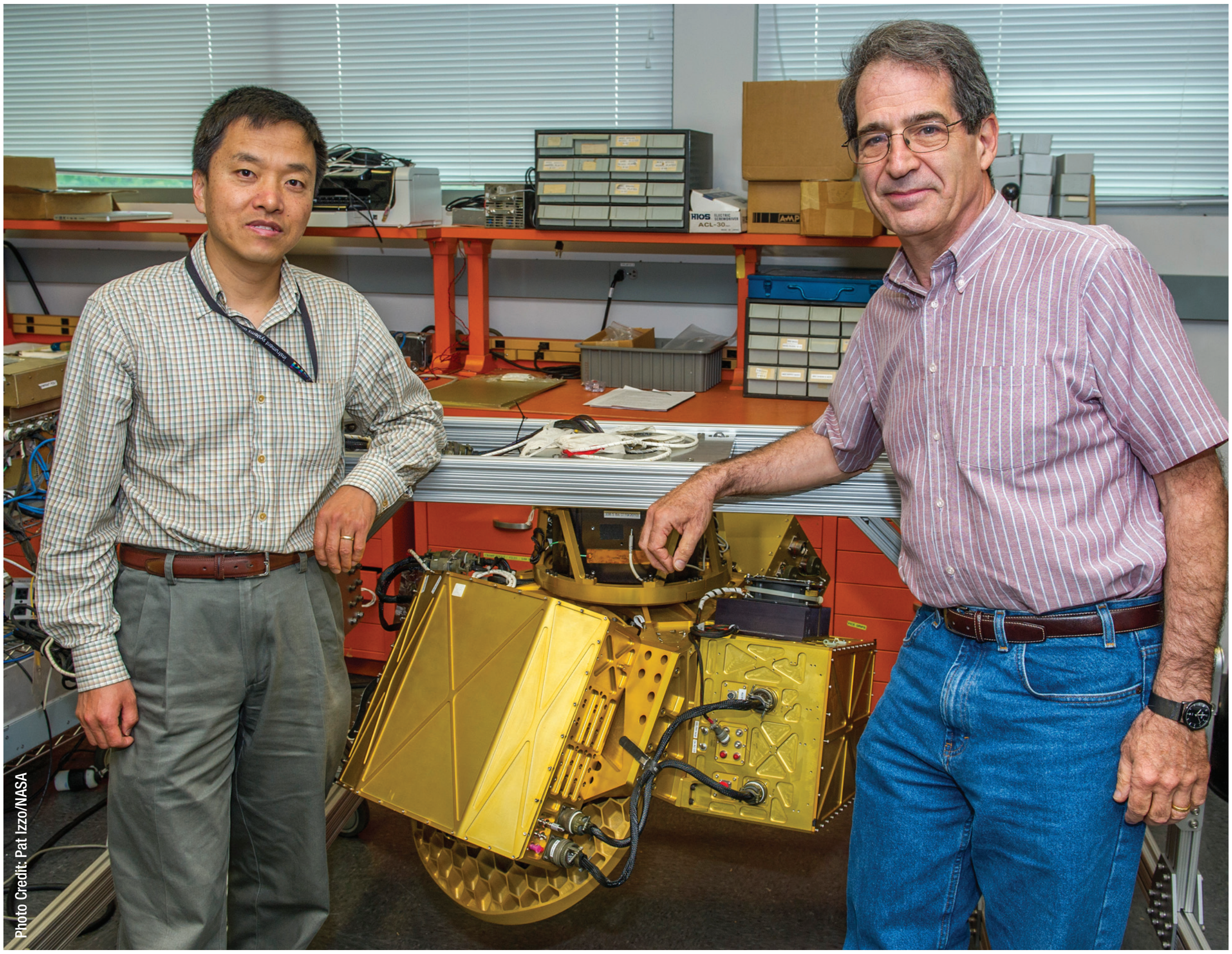
New Doppler Radar Debuts on 2013 HS3 Mission



Engineer Lihua Li and Scientist Gerry Heymsfield have been working on the HIWRAP radar since 2005.

Most aircraft carrying Doppler radar look like they've grown a tail, developed a dorsal fin, or sprouted a giant pancake on their backs.

But when the unmanned Global Hawk aircraft carries a radar system this summer to gather hurricane data, its cargo will be hard to see. The autonomous and compact High-altitude Imaging Wind and Rain Profiler (HIWRAP), a dual-frequency conical-scanning Doppler radar, will hang under the aircraft's belly as it flies above hurricanes to measure wind and rain and to test a new method for retrieving wind data.

"Radar is one of the most important types of remote sensors for atmospheric research," said Lihua Li, a Goddard engineer who helped develop HIWRAP, which was funded in part by NASA's Instrument Incubator Program and Goddard's Internal Research and Development (IRAD) program.

"Radar signals penetrate clouds and precipitation, allowing scientists to collect information on raindrops or ice particles, which in turn allows scientists to understand weather events," Li said.

This past year, Li and his colleagues used additional IRAD funding to further advance HIWRAP's radar technology, making it more effective at high altitudes. The updated HIWRAP instrument will test its new capabilities for the first time this August and September as part of the Hurricane and Severe Storm Sentinel (HS3) mission (see related story, page 7).

The ultimate goal, Li said, is applying the new radar technology to measure weather events from space.

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Building a Better Radar

Before fully appreciating the team's accomplishments, Li says it's important to understand how radar works. Under these systems, a transmitter pulses microwaves into the atmosphere. After they strike a target, they break apart into many return microwave frequencies, which then bounce back to the instrument. The returning frequencies contain magnitude and phase information that identifies the targets as rain, ice, or a mix. They also reveal water content and the size, shape, and distribution of the particles. Most importantly, radar's ability to see through clouds gives a three-dimensional image — from the cloud top to the ground — of what's going on inside storms and hurricanes.

> ***"Radar is one of the most important types of remote sensors for atmospheric research. Radar signals penetrate clouds and precipitation, allowing scientists to collect information on raindrops or ice particles, which in turn allows scientists to understand weather events."***
>
> ***— Lihua Li***

To generate and send a rapid number of microwave pulses, radars generally need a lot of power. For better sensitivity and accuracy, they need big antennas. But radars flying high above Earth's surface have strict limits on size, weight, and power consumption, Li said.

All these things had to be balanced against the science requirements for HIWRAP, which was designed to fly on the Global Hawk. Since 2005, Li and Gerry Heymsfield, who leads Goddard's High Altitude Radar group, have pushed the design envelope with HIWRAP. They began with using compact, less power-hungry transmitters, a more flexible digital receiver, and a scanning antenna that widens HIWRAP's area of view below. Looking a bit like an upside-down golden flower, HIWRAP weighs in at about 300 pounds and has a footprint the size of a small washing machine.

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HS3 Open for Hurricane Season

This isn't the first rodeo for Goddard's High-altitude Imaging Wind and Rain Profiler (HIWRAP).

In fact, its flight as one of six instruments on NASA's Hurricane and Severe Storm Sentinel (HS3) mission later this summer will be its fourth go at measuring wind and rain in big storms. This time, however, the dual-frequency Doppler radar will employ advanced technologies that scientists hope to one day incorporate into a space-based mission (see related story, page 6).

"The goal of HS3 is understanding how hurricanes intensify and to actually capture data while they're intensifying," said Gerry Heymsfield, lead scientist for the High Altitude Radar group that developed HIWRAP, which made its debut on NASA's Global Hawk aircraft in 2010 as part of the Genesis and Rapid Intensification Processes campaign (*Goddard Tech Trends,* Summer 2010, Page 4). HIWRAP then flew in 2011 on NASA's ER-2 aircraft over storms in Oklahoma to help scientists develop algorithms for the upcoming Global Precipitation Measurement mission and then again in 2012 during HS3's test flights over the Pacific Ocean.

Photo Credit: NASA Wallops

NASA's Global Hawk lifts off the runway at Wallops Flight Facility during the 2012 HS3 mission, which investigated Tropical Storm Nadine near the Azores Islands in the eastern Atlantic Ocean.

For the HS3 mission later this summer, scientists will install HIWRAP on one of two Global Hawk aircraft, which are remotely piloted from Wallops Flight Facility in Virginia and Dryden Flight Research Center in California. HIWRAP will detect winds by observing the motion and speed of precipitation

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Doppler, *continued from page 3*

But most significant are new advancements that push the boundary of radar capability, both from high-altitude and long-endurance flights on unmanned aircraft such as the Global Hawk. The scanning antenna allows the use of two pulse beams at different angles to the ground. Each of the two beams sends out pulses at two different radar frequencies, and the combination means that HIWRAP is capable of imaging the volume of precipitation particles from Earth's surface to the cloud tops. In addition, HIWRAP can measure the Doppler effect of precipitation particle movement.

Blowing in the Wind

The Doppler effect describes the change in frequency of waves that reflect off a moving object, the same effect that causes sound from a car or train to change as it moves closer or farther away from a listener. Scientists interested in raindrops or other atmospheric particles use the same principle. Doppler radar sends out pulses of microwaves whose frequency will shift when they bounce off moving raindrops, and scientists use this to figure out how fast ice or rain is moving in storms.

Detecting movement of rain and other precipitation tells scientists about another piece of the atmospheric puzzle — wind. With Doppler, "we sense the motion of rain or ice particles in storm clouds. From that we can get the horizontal winds and the circulation in hurricanes," said Heymsfield, who has been working to improve high-altitude radar measurements for 20 years.

Doppler measurements also have been used to estimate the size of the rain or ice particles. Together with the wind data, HIWRAP provides data sets on tropical cyclones critically needed for improved understanding and forecasting these weather events, Li said.

Straightforward, Yet Challenging

While Doppler physics is straightforward, in reality it's difficult measuring precipitation's Doppler signal, Li said. One difficulty is that the return frequencies from the target rainfall and clouds come back with a clutter of other things that also bounce back a signal, like the ground or ocean surface. "To get the Doppler velocity of rain, for instance, you then have to separate all those signals," Li said.

An added complication arises when the radar is on an aircraft or a satellite. "The instrument itself

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Hurricane, *continued from page 7*

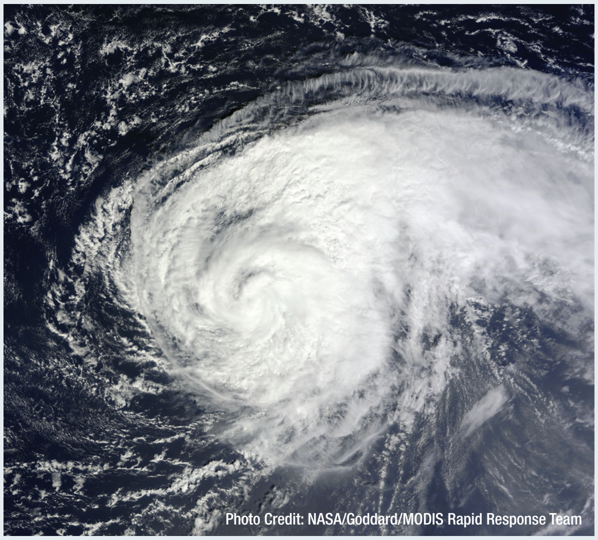

Photo Credit: NASA/Goddard/MODIS Rapid Response Team

NASA's Terra satellite captured this true-color image of Hurricane Nadine in the Atlantic Ocean on Sept. 16, 2012 while NASA's Global Hawk flew around the storm as part of last year's HS3 mission.

particles in the clouds below. "The motion of the particles is more or less the actual wind," Heymsfield said, adding that the measurements reveal information about the storm's circulation, which scientists then use to further their understanding of hurricanes and, eventually, improve their ability to forecast severe storms.

Also to be deployed are the Goddard-developed Cloud Physics Lidar, developed with Goddard Internal Research and Development (IRAD) program funding, the scanning High-resolution Interferometer Sounder, and the Advanced Vertical Profiling System dropsondes. The second Global Hawk, flying to about 60,000 feet, will carry HIWRAP, the Hurricane Imaging Radiometer, and the High Altitude Monolithic Microwave Integrated Circuit Sounding Radiometer.

"Our goal with the environmental flights is to see how storms are affected by or interact with their nearby environment, including sources of dry air, Saharan dust, and vertical wind shear," says Scott Braun, HS3 principal investigator.

A third IRAD-funded instrument, the Tropospheric Wind Lidar Technology Experiment, will fly on the Global Hawk during the HS3 mission in 2014. ❖

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Doppler, *continued from page 8*

is moving, so it also has Doppler information," Li said. The fast-moving platform with a high ground speed causes an increase in the magnitude of the Doppler shift and the range of frequencies returned for each target. "This makes the retrieval of rain or ice-particle Doppler velocity extremely difficult," Li said. The aircraft Doppler effect has to be distinguished from the Doppler effect of the target. Imagine trying to measure the velocity of a toy train with an instrument whizzing by on a full-size train 12 miles away, the height of a high-altitude plane. Or, imagine taking measurements from 250 miles away, the altitude of a satellite in space.

One way to get a better return signal from high-altitude aircraft is to send out more radar pulses, more quickly. For a satellite passing over the ground at about 12,000 miles per hour, it's even more important to have a rapid series of pulses. But too many pulses per second can muddy the measurement if the returning Doppler-shifted frequencies overlap.

Scientists need a way to distinguish which returning frequency corresponds with which emitted pulse. For HIWRAP's upcoming HS3 mission, Li and his team will test a method of putting an identifier on each outgoing microwave pulse.

He and his colleagues will incorporate the necessary modifications to the outgoing radar pulses into HIWRAP's transmitter and receiver. While the technique has the potential to improve measurements on any Doppler radar, especially those on aircraft, its true impact will be on next-generation precipitation-measuring satellite radars that will view rain worldwide every few hours. Currently, only two satellites carry radar in space and neither returns particle-motion data. "Doppler implementation will be the next step," Li said. "That's what we are pushing for." ❖

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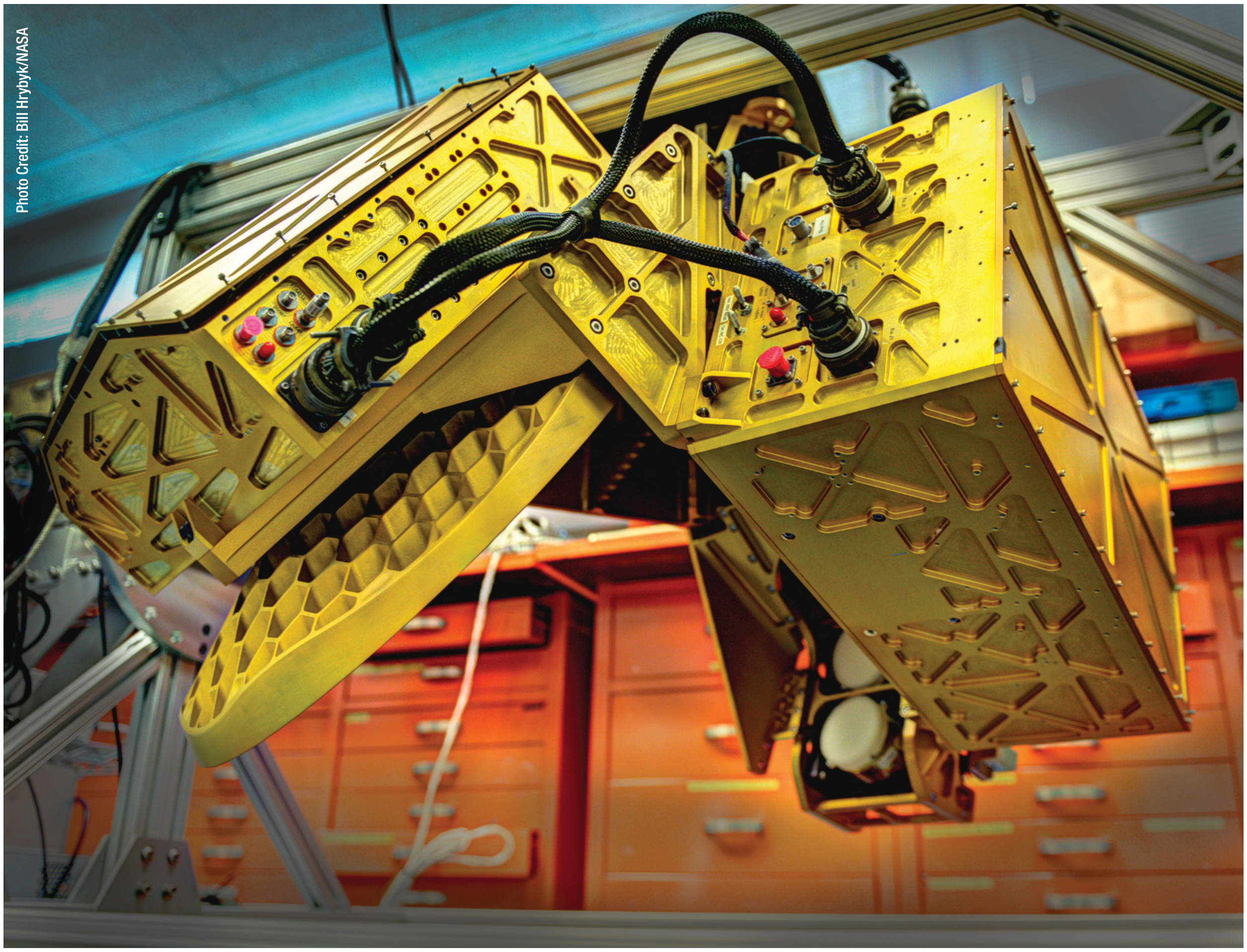

Photo Credit: Bill Hrybyk/NASA

The HIWRAP dual-frequency Doppler radar will hang under the Global Hawk. On the left, the golden disc is the antenna and on the right, the two small white discs are the radar-beam transmitters, one for each frequency. The whole apparatus spins while flying.

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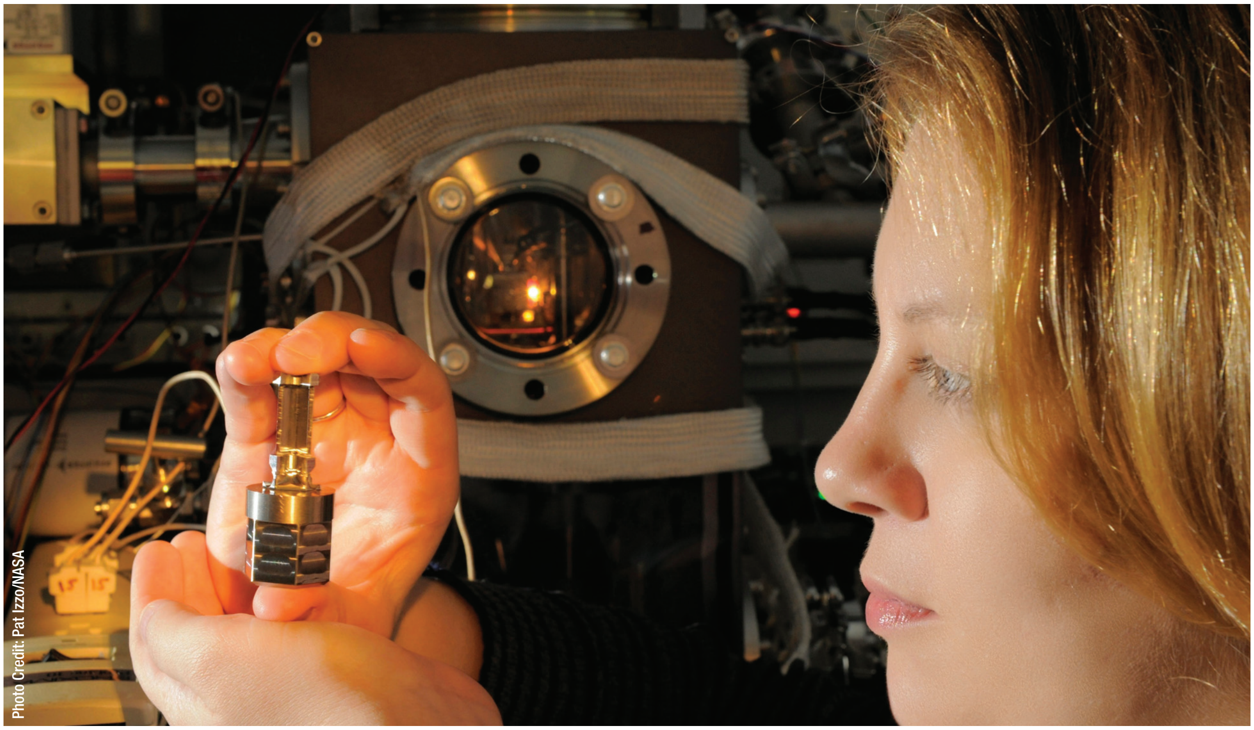
Power of Leverage

Scientist Wins Millions to Develop Next-Generation Mass Spectrometer



Veronica Pinnick, Will Brinckerhoff's colleague, holds one of the highly compact mass spectrometer rods, the heart of Brinckerhoff's Linear Ion Trap Mass Spectrometer.

No one needs to convince Will Brinckerhoff of the power of leverage.

Had Goddard not already begun developing instrument components for a European Space Agency (ESA) mission to Mars and had it not already invested in a powerful sample-analysis technology, it's possible that the Goddard scientist wouldn't have won a whopping $3 million in NASA research and development funding to advance a miniaturized instrument capable of in situ characterization of a wider range of complex organic and inorganic compounds locked inside Martian rock and other extraterrestrial samples.

With the three-year funding from NASA's Maturation of Instruments for Solar System Exploration (MatISSE) program, Brinckerhoff's team plans to advance the next-generation, highly compact Linear Ion Trap Mass Spectrometer (LITMS) to the point where it could be chosen to fly on a future NASA rover mission in search of signatures of life on Mars.

"LITMS will enable in situ characterization of organics and elements in individual rock core layers," said Brinckerhoff, a Goddard scientist who won the multi-million-dollar MatISSE award. "Our instrument's unprecedented level of integrated analytical capability is critically needed to achieve NASA's astrobiology objectives at Mars."

Leverages MOMA-MS and Pyrolysis Oven

The instrument takes advantage of significant developments by a Goddard team helping to build the Mars Organic Molecule Analyzer-Mass Spectrometer (MOMA-MS) scheduled to fly on ESA's 2018 ExoMars mission. Led by Germany's Max Planck Institute for Solar System Research, MOMA-MS will identify organic material by measuring the mass of the individual molecules bound up inside Martian rock and soil samples.

To measure their characteristics, the instrument will zap samples with a high-intensity laser that converts the molecules into ions — a state where they lose or gain an electron. Once formed, these ions then are electrostatically directed into a mass analyzer where they are separated according to their mass and charge. The result is a spectrum that can identify the elements and structural details that make up the molecules.

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One of the instrument's distinguishing features is its sample processing-and-handling technology developed by Manhattan-based Honeybee Robotics Spacecraft Mechanisms Corp. This device drills into rock to extract a one-centimeter cylindrical core sample that the instrument's pulsed laser then zaps to ionize nonvolatile molecules — such as heavier hydrocarbons — that the mass spectrometer then analyzes. The capability will allow scientists to analyze any of the sample's layers, with point-by-point precision.

The other technology Brinckerhoff is leveraging is a pyrolysis system that Goddard scientist Danny Glavin developed for the Volatile Analysis by Pyrolysis of Regolith (VAPoR) instrument, funded in part by Goddard's Internal Research and Development program. VAPoR is a miniaturized version of Goddard's Sample Analysis at Mars (SAM) instrument suite now carrying out investigations from its berth on NASA's Curiosity rover.

While SAM is analyzing gases to determine whether they contain organic compounds necessary for life, VAPoR originally was designed to search for volatiles, like water, oxygen, and noble gases, at high-priority astrobiological targets, including the Moon, Mars, and small bodies, such as asteroids and comets.

Both SAM and VAPoR employ miniature ovens that heat powdered soil and rock samples to temperatures that would melt aluminum. As the samples heat, they release gases that the instruments then analyze. A significant difference between the two, however, is that VAPoR's pyrolysis system is dramatically smaller, and therefore, capable of heating to even higher temperatures for a given power level (*Goddard Tech Trends,* Summer 2011, Page 6).

New Bells and Whistles

"What we're doing is combining the MOMA mass spectrometer, the VAPoR pyrolysis system, and a precision sampler," Brinckerhoff said, adding that the laser and pyrolysis technologies will be linked through a single, highly miniaturized linear ion trap mass analyzer, as they are on MOMA. "Basically, the last five years of instrument development is getting shoe-horned into this," he said.

By combining these capabilities into one compact package, the result is a more capable instrument, Brinckerhoff said.

In contrast to MOMA-MS, LITMS will be able to take pinpoint measurements of the surfaces of the rock cores using its focused, high-intensity laser. It also will be able to use VAPoR's pyrolysis technique to analyze a small amount of powder collected with a novel Dremel-like grinding wheel. The compounds will be sent to a gas chromatograph column and then to an electron-ionization source, similar to the one used by SAM and VAPoR. "We're combining both methods of sampling and heating to have the best chance of identifying complex compounds, like polymers, or any organic 'goop,'" Brinckerhoff said.

This image is a close up of the core-sampling drill to be used on a next-generation mass spectrometer that leverages recent R&D program-funded technological advances.

In addition, the LITMS mass spectrometer will be able to analyze both positive and negative ions, which broadens the range of molecules the instrument will be able to identify. The mass range will be expanded, as well. MOMA-MS identifies chemicals with an atomic mass of 50 to 1,000 Daltons. LITMS, on the other hand, will be able to identify those with an atomic mass of 20 to 2,000 Daltons, Brinckerhoff said.

"The story is we can analyze individual layers or features in a heterogeneous rock core, using two complementary methods, and now we're able to measure the widest variety of molecules," he said. "The science and the design go hand in hand. We've put together an elegant and efficient design that does a lot in a small space." ❖

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New Circuit Handles Common, Yet Essential Housekeeping Tasks

George Suarez (seated) and Jeff DuMonthier have combined multiple housekeeping-type functions onto a single, relatively small radiation-hardened integrated circuit, which measures slightly more than an inch on a side.

Housekeeping may not be fun, but someone has to do it.

The same can be said for the sensors and associated electronics that carry out these all-important, behind-the-scenes tasks onboard spacecraft. For instrument and spacecraft avionics, they control important functions and monitor the health and safety of systems, spotting anomalies before they become big problems for mission scientists. Until now, these health-monitoring sensors would connect to multiple, discrete components that would perform switching, amplification, digitization, processing, and storage tasks.

Needless to say, this cornucopia of parts could consume a lot of mass, volume, and power.

Multiple Functions on a Single Die

Now, a team of Goddard technologists has combined these multiple functions onto a single, relatively small radiation-hardened integrated circuit, which measures slightly more than an inch on a side. The so-called Housekeeping-on-a-Chip, which is now undergoing testing, promises to simplify the circuitry that helps monitor everything from voltages and currents to temperature levels. And in doing so, it could help reduce the size, mass, and cost of space missions. This device implements a microprocessor, on-chip storage memory, analog-to-digital and digital-to-analog converters, as well as serial communications, all while consuming less than half a watt of power.

Funded by NASA's Space Technology Mission Directorate's Game Changing Program, the team used as its foundation the Sandia National Laboratories' "structured" application-specific integrated circuit (ASIC), which is hardened against radiation-

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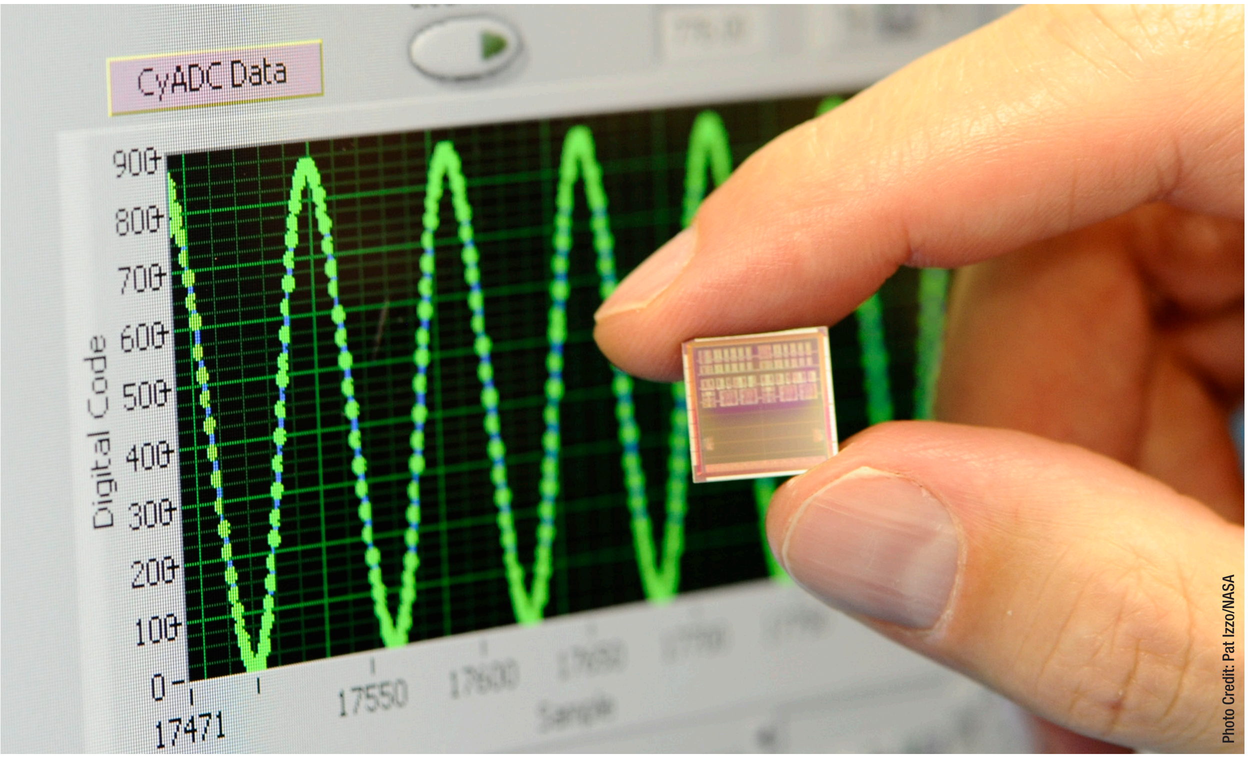

This is a close-up of the Housekeeping-on-a-Chip, which promises to simplify and reduce the circuitry that helps monitor everything from voltages and currents to temperature levels. In doing so, it could help reduce the size, mass, and cost of space missions.

induced effects that wreak havoc on commercially available circuits. ASICs typically are designed to perform a particular job, but Sandia's structured ASIC is general purpose, providing users a platform from which to economically customize the jobs they want the technology to do.

Because they are radiation hardened and fabricated en masse, the structured ASICs offer a less expensive and more readily available option for mission planners and instrument developers, who otherwise must develop one-of-a-kind, highly customized circuits that can cost millions of dollars.

The team, which also includes Goddard technologists Wes Powell, George Suarez, Jeffrey DuMonthier, Robyn King, George Winkert, and Salman Sheikh, began work on the housekeeping chip two years ago after learning of Sandia's capability. "They are extremely radiation hardened," Powell explained. "We thought it might be applicable for a system-on-a-chip, where the analog and digital circuitry, microprocessor, memory, and controllers were all on a single die."

Shows Promise

Understanding the potential Sandia's circuit offered, the team set out to create a system-on-a-chip, choosing housekeeping tasks because all spacecraft and instruments require the capability, Suarez said. "We asked what does everyone use the same way," DuMonthier added.

Using the structured ASIC as the foundation, the team then configured the chip so that it could handle the housekeeping tasks needed by most missions. Now in testing, the team says the system-on-a-chip shows promise.

"What we've done is built up a generic device. What this means is that we can develop these systems faster and cheaper and confine these multiple tasks to one circuit," Powell said. "This holds great potential to dramatically reduce the size and complexity of housekeeping-related circuitry, offering instrument and subsystem developers a low-power, low-cost alternative to more traditional approaches." ❖

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Orbit, *continued from page 3*

When the spacecraft is at the lowest point closest to Earth, it remains well above geosynchronous orbit 22,236 miles above the equator where most communications satellites operate. At this lowest point, or perigee, TESS will orient its dish antenna to Earth and transmit data to ground stations below, a process that will take three hours. At its highest point, or apogee, some 264,000 miles above Earth, it avoids the hazards posed by the Van Allen radiation belts, which extend from about 621 to 37,282 miles above the surface.

"This is the first time this orbit has been used," said Trevor Williams, a Goddard engineer who played a pivotal role in evaluating the trajectory's appropriateness for the TESS mission. "It's a stable orbit, stable in the sense that it isn't plagued by attitude perturbations."

Continued on page 15

Traveling, *continued from page 3*

of parameters, such as the spacecraft's point of origin, its final destination and physical characteristics, as well as a range of launch dates and flight times.

The software tool then uses these data points to calculate the most efficient trajectory, including the number of flybys, for reaching a celestial target, whether it is a moon in the outer solar system or a Kuiper Belt object. Better yet, Englander said, the tool can calculate many different possible trajectories at a time, depending on which parameters a mission planner uses. "This dramatically reduces time to calculate a mission configuration," he added.

The tool, which comes in two different versions to calculate the trajectories of chemically (high-thrust) or electrically (low-thrust) propelled spacecraft, is effective, too, Englander said. "The high-thrust (chemical propulsion) version of this EMTG has already achieved a number of successes," Englander said.

Without knowing the precise maneuvers that NASA's Cassini-Huygens mission used to reach Saturn and its moons, Englander used his tool to calculate the mission's flyby sequence and trajectory. "It took only two days of computing time on an ordinary desktop computer and no other user input to reproduce the Cassini mission configuration — a trajectory that originally took extremely talented designers many months to develop."

Now that he has shown its effectiveness, Englander said he plans to further improve the EMTG's fidelity. "The purpose of EMTG is to enable the design of new types of missions and reduce costs. Anyone can use this tool." ❖

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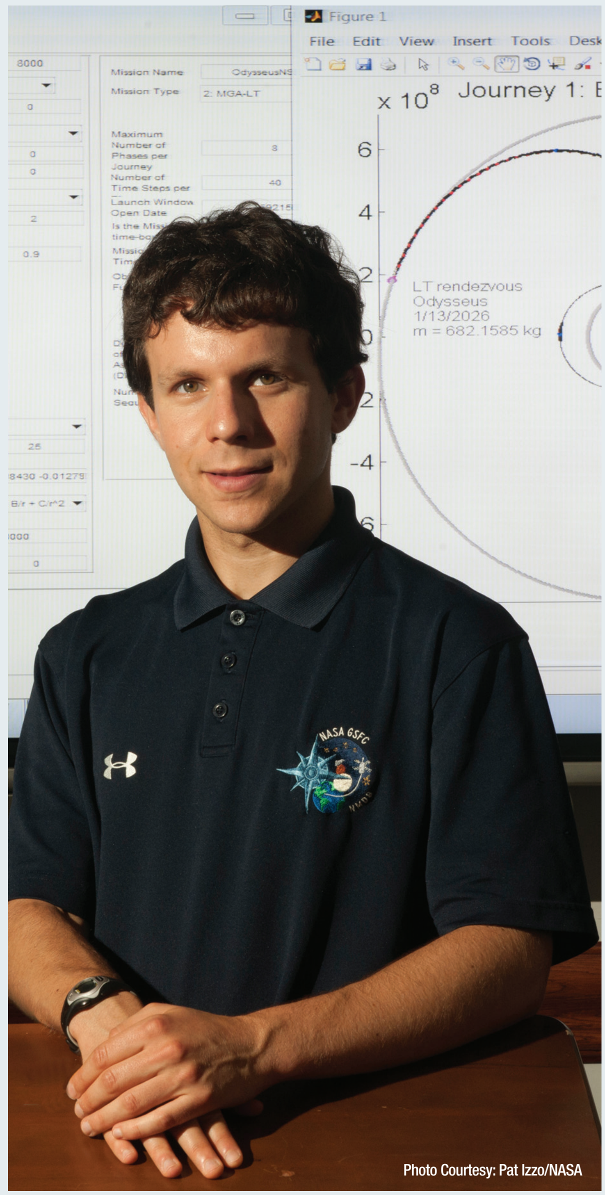

Photo Courtesy: Pat Izzo/NASA

Jacob Englander has created an orbit-determination tool. The image projected in the background shows the trajectory to Odysseus, a Trojan asteroid. While not associated with any mission or mission proposal, Englander used his tool to create the design because one of his coworkers suggested that it was a difficult-to-reach target.

Orbit, *continued from page 14*

Papers Pave Way

Although lunar-resonant orbits were first discussed in the early 1990s, TESS's particular trajectory was based on the original work of Goddard contractors Daniel McGiffin and Michael Matthews, both from the Computer Sciences Corporation, and Goddard engineer Steven Cooley. In 2001, the team published a paper describing their research into lunar-resonant orbits and explaining why they were ideal for a range of space missions.

Specifically, the paper reported that at lunar-resonant orbits, perturbations from the gravitational tug-and-pull exerted on spacecraft by the Moon and Earth are roughly zero, especially if the spacecraft's apogee is about 90 degrees with respect to the Moon. As a result, these highly elliptical high-Earth orbits offer long-term stability for spacecraft. Once a satellite reaches the trajectory, few, if any, station-keeping maneuvers are required to keep it there — a particularly attractive option for mass-constrained spacecraft that can't carry propellant to periodically power thrusters to maintain an orbit.

In 2010, two members of the TESS team — OSC's Jose Guzman and Robert Lockwood — realized the importance of the 2001 Goddard paper. They suggested to Ricker, who already was searching for a way to provide TESS with an uninterrupted view of the cosmos, that the mission consider using the P/2 orbit. Ricker agreed, tapping Goddard engineers Dave Quinn and Mark Woodard to calculate the preliminary orbital maneuvers required to place TESS into its final P/2 orbit.

Then in 2011, Goddard engineer Donald Dichmann, who at the time worked for Applied Defense Solutions, and his co-authors began work on a paper reviewing the trade studies NASA made when it decided to move its Interstellar Boundary Explorer from its original orbit to a more stable position at another lunar-resonant orbit — P/3 — where it's mapping the boundary between the solar system and interstellar space. In their paper, which was published in 2012, Dichmann and his co-authors concluded that it "would be interesting to examine" other lunar-resonant orbits like TESS's P/2 orbit.

"Ricker saw that paper and said 'let's repeat that refined stability analysis for the TESS orbit,'" Dichmann recalled.

Months-Long Study

During TESS's Phase A study in 2011-2012, additional members of the Goddard's world-renowned Navigation and Mission Design Branch joined forces with Ricker and began a months-long investigation examining the details of the P/2 orbit and the precise maneuvers needed to deliver TESS to this "distinctive orbit."

The evaluation by the combined TESS team, involving sophisticated orbit-determination tools (see related story, page 3), confirmed that the orbit offered a relatively clear view of the cosmos, good visibility of ground stations, little contamination from straylight, and a benign, low-radiation environment — all important ingredients for a productive all-sky survey cataloguing extrasolar planets around bright stars. Just as important, the team concluded that once TESS reached its P/2 orbit — through a series of maneuvers also involving a lunar flyby to gain momentum from the Moon's gravity — it would remain stable in that orbit for several decades.

Further analysis funded by Goddard's Internal Research and Development program revealed that the orbit afforded a far greater number of actual launch days than originally envisioned. "One of the most significant things we accomplished, and Trevor (Williams) played a key role, was determining that, at its farthest point, the spacecraft-Earth-Moon angle doesn't need to be 90 degrees, but can vary as much as 30 degrees from that and still provide a stable orbit," said Chad Mendelsohn, a Goddard engineer involved in the orbit studies.

As a result, the mission will enjoy many more launch opportunities. In fact, in any given 27-day lunar cycle, the TESS team will be able to launch on 23 of those days. "We relaxed the orbit constraints and really opened up the launch window," Mendelsohn said.

Indeed, TESS will take advantage of a number of innovations, one of the most significant being its never-before-used orbit, Ricker said. "For TESS, we were able to devise a special new 'Goldilocks' orbit for the spacecraft, one which is not too close, and not too far from both the Earth and the Moon," Ricker said. ❖

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Team Wins Cubesat Berth to Gather Energy-Imbalance Measurements

A team of scientists has won a berth on a tiny satellite to explore the imbalance in Earth's energy budget and the extent to which fast-changing phenomena, like clouds, contribute to that imbalance.

NASA's In-Space Validation of Earth Science Technologies (InVEST) program has funded a team led by Lars Dyrud, chief scientist for Earth Science at the Boston-based Draper Laboratory, to develop a miniature instrument that will measure the amount of solar energy reflected by Earth and the amount emitted to space as infrared radiation or heat (*CuttingEdge,* Winter 2013, Page 4).

The mission, called the Radiometer Assessment using Vertically Aligned Nanotubes (RAVAN), will fly on the Johns Hopkins University Applied Physics Laboratory's (APL) Multi-Mission Nanosatellite, a diminutive spacecraft that measures only four inches wide and 13 inches long. The team includes Goddard scientists Warren Wiscombe and Dong Wu; APL, which is constructing the tiny satellite and integrating RAVAN; and the New Windsor, Md.-based L1 Standards and Technology, Inc., which is building the instrument. A launch date has not been set.

Widely cited papers have concluded more energy is being absorbed from the sun than is emitted back to space, throwing the Earth's energy "out of balance" and warming the globe. Instead of just warming the air, scientists believe the extra energy mostly warms the ocean, although a sizeable fraction of it has been reflected back to space by the increasing activity of small volcanoes that create stratospheric aerosol. In fact, surface temperatures, considered the gold standard in detecting global climate change, have flat-lined since the great El Niño of 1998, which caused an unprecedented spike in warming, Wiscombe said.

With the InVEST funding, the team plans to demonstrate a new technique for measuring Earth's radiation budget. The team is building a radiometer — an instrument that measures the flux of electromagnetic radiation — and equipping it with a next-generation detector made of carbon nanotubes, which are tiny hollow tubes grown vertically on silicon and other materials. Advanced by Goddard technologists, the technology is highly efficient at absorbing and trapping light across multiple wavelength bands — so efficient, in fact, that only a tiny fraction of the light actually escapes (see related story, page 4).

"If you want to measure outgoing radiation with the accuracy necessary to improve our predictions of global climate change, you have to make measurements everywhere, all the time," Dyrud said. "This carbon-nanotube radiometer allows us to do this accurately and in a small enough form that it fits inside a nanosatellite, which is a necessary development that makes these measurements possible and affordable."

With this application, radiation leaving the Earth, both reflected solar and emitted infrared, would strike the radiometer's Vertically Aligned Carbon Nanotube (VACNT) detector, which, in turn, would absorb the radiation and measure its own change in temperature, providing scientists with a more comprehensive picture of Earth's radiation budget. The team plans to test the VACNT detectors next summer aboard a commercial suborbital vehicle that takes off and lands vertically.

Obtaining funding to fly the radiometer on APL's tiny spacecraft is just the first step, however. The team believes Earth radiation-budget science ultimately will require scores of radiometers installed on massive satellite constellations, which would be more easily realized by flying the instruments on less-expensive nanosatellites, Wiscombe said. ❖

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Cutting edge Goddard's Emerging Technologies

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