NAVAL SCIENCE AND TECHNOLOGY

FUTURE FORCE™

VOL. 5, NO. 4, 2019

THE U.S. NAVAL RESEARCH LABORATORY

IN SPACE

VOLUME 5
#04
2019

FUTURE FORCE

NAVAL SCIENCE AND TECHNOLOGY MAGAZINE




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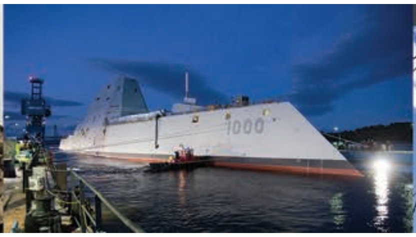

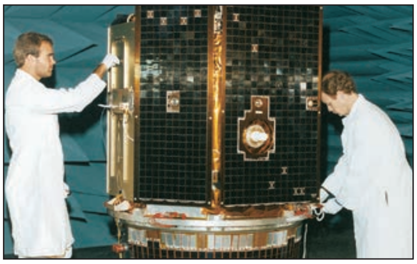

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Front Cover: An artist's concept of NASA's Parker Solar Probe, launched in 2018 carrying the Naval Research Laboratory's Wide-Field Imager for Solar Probe (WISPR) instrument, a revolutionary mission to go deep in the heart of the sun's corona.

SPEAKING OF S&T

▶▶ Dr. Gurpartap S. Sandhoo

Photo by NRL

It was St. Patrick's Day, 17 March 1958, when the U.S. Naval Research Laboratory (NRL) launched Vanguard I, the Navy's first Earth-orbiting satellite.

For that launch, the laboratory's researchers and engineers designed and developed a three-stage rocket and a Minitrack network to track the satellite using radio interferometry. The small aluminum sphere they launched (16.5 centimeters in diameter) remains the oldest man-made object in space. (The world's first artificial satellite, Sputnik 1, fell back to Earth three months after its launch.)

While the Vanguard today may be remembered as NRL's first historic achievement in space operations, the launch was far from NRL's first space venture. It was more than a decade earlier. NRL's space operations began in 1946, when the lab was invited to participate in the U.S. Army's V-2 rocket program. With the lab operating as the chief agency for research and mission technology, 80 experiments were performed between 1946 and 1951.

Using German rockets captured by American forces at the end of World War II, NRL's researchers and engineers pioneered space-based atmospheric research and astronomy, achieving the first detection and measurement of solar X-rays and taking the first photos of Earth from 40, 70, and 101 miles above the Earth.

With those experiments, the lab set out to form a major space science program and, within a decade, established a base of rocket science for the development of scientific payloads and new rocket technology.

As you will see in this special issue of *Future Force*, we at NRL are still hard at work more than seven decades later. In anticipation of the 35th Space Symposium, we are excited to present this compelling cross-section of history and just a taste of the laboratory's ongoing research and history.

The stories you will find in these pages span a range of space research issues, including the lab's ongoing research on the ever-growing problem of space debris. In that story, we look at the work NRL physicists are doing to harness the big data of space debris, and we spotlight a new project for a space-based instrument that will identify the debris in orbit that poses a growing threat to spacecraft.

Elsewhere, we look back the launch 25 years ago of NRL's Deep Space Program Science Experiment—better known as "Clementine"—a mission that produced the first global topographic map of the moon. In another, we admire the amazing imagery from the Sungrazer project, a citizen science initiative that studies comets that pass extremely close to the sun.

This issue also highlights the work of NRL researchers with the Fermi Gamma-ray Space Telescope Collaboration, which is measuring the rate of star formation to gain insight into the origins of the universe.

For additional information about NRL's latest research, including photos, stories and videos, please visit NRL's website at https://www.nrl.navy.mil/space/.

Dr. Sandhoo is the superintendent of the Spacecraft Engineering Department at the U.S. Naval Research Laboratory.

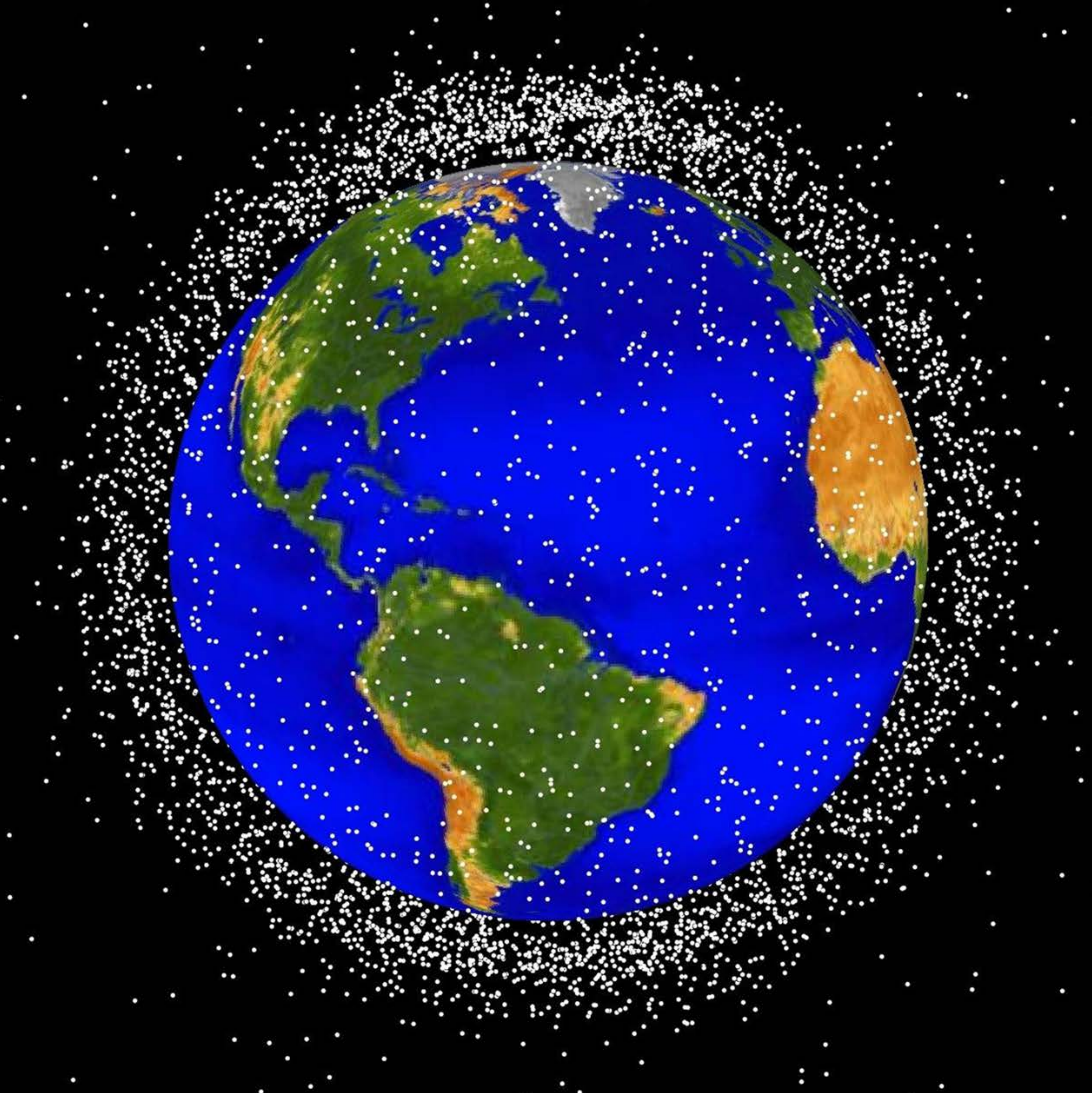
THE U.S. NAVAL RESEARCH LABORATORY IN SPACE

Launched in earliest months of the Space Age, Vanguard was the culmination of more than a decade of planning, research, and testing at NRL.

EYES ON THE SKIES

NRL RESEARCHERS TACKLE THE EVER-GROWING PROBLEM OF ORBITAL DEBRIS

By Emanuel Cavallaro



HUMANS HAVE LEFT JUNK IN SPACE SINCE THE BEGINNING OF THE SPACE AGE. PARTICLES OF DEBRIS FROM SEVEN DECADES OF MISSIONS NOW RUN INTO THE THOUSANDS. TRACKING IT ALL, AND DETERMINING WHAT TO DO WITH IT, ARE ISSUES THAT CONTINUE TO CHALLENGE RESEARCHERS.

It was 11 January 2007 when China launched a ballistic missile at its defunct weather satellite, Fengyun 1-C, setting off an explosion that marked the largest manmade creation of space debris in the history of space exploration. The destruction sent more than 3,000 pieces of trackable debris and an estimated 150,000 debris particles encircling the Earth.

China's antisatellite missile test wasn't the first of its kind. The United States had conducted a similar test in 1985, when it used an antisatellite missile to destroy its Solwind P78-1 satellite at 555 kilometers altitude. Nevertheless, China's destruction of Fengyun 1-C occurred at about 850 kilometers altitude, well above the Earth's atmosphere, ensuring that most of the fragments would remain in orbit for decades.

Blossom Point Tracking Facility antennas point skyward at sunset.Photo by Emanuel Cavallaro

While historic, the Fengyun event is just one conspicuous feature of an increasingly complex international problem, one with no easy solution. The space debris population has grown in size since the earliest days of spaceflight, when the U.S. Naval Research Laboratory's (NRL's) Minimum Trackable Satellite (Minitrack) receivers began tracking the first manmade objects to go into orbit—Russia's Sputnik in 1957, then NRL's own Vanguard satellite in 1958.

Today, the operational community is tracking more than 20,000 objects larger than 10 centimeters in the official satellite catalog, while the estimated population of objects between one and 10 centimeters in diameter runs to 500,000, according to NASA's Orbital Debris Program Office. Though the probability of a collision between a spacecraft and debris today remains incredibly low, such a collision with an object as small as a paint fleck has the potential to disrupt or even end a space mission.

The rate of collisions also has the potential to increase exponentially, according to retired NASA scientist Donald J. Kessler, who founded the Orbital Debris program office. In 1978, he proposed a theory now known as the "Kessler Syndrome" that debris generated by a collision could cause even more collisions, leading to a runaway cascade of collisions that would create a massive debris field in low Earth orbit, posing a real threat to the future of space operations. The catastrophic consequences of such a series of events were dramatically illustrated in the 2013 movie *Gravity*.

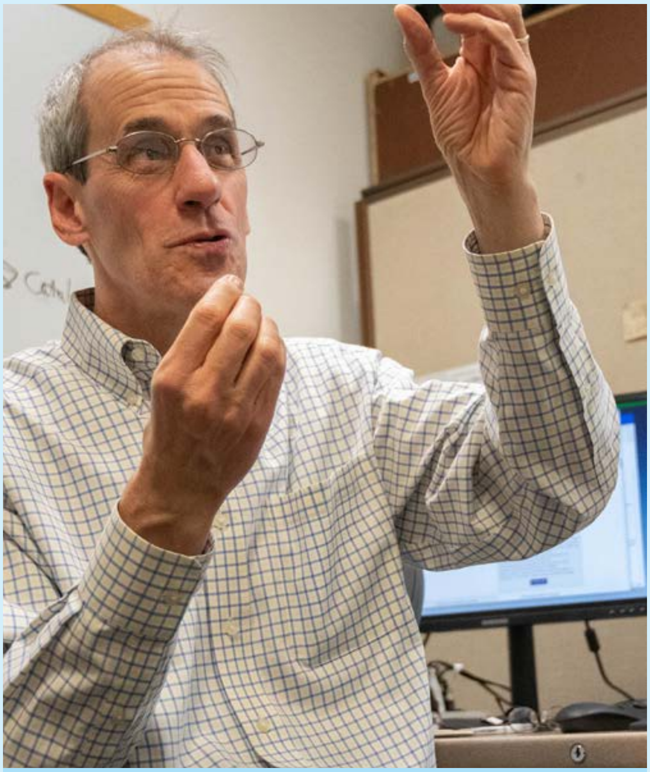
At NRL, aerospace engineers, astrodynamicists, research physicists, and others are working in concert with the Air Force, NASA, and other partners to approach the problem in a number of ways, beginning with NRL's Mathematics and Orbit Dynamics Section. There, researchers are collaborating with government partners and the private sector to track orbital debris while preparing for the completion of a new space fence that will radically transform our view of orbital debris from Earth.

Meanwhile, engineers with NRL's Geospace Science and Technology Branch are developing a space-based optical instrument that can detect orbital debris. At the Blossom Point satellite tracking facility in Maryland, NRL's high-precision, orbit-determination software is contributing to reliable "lights out" operations that ensure spacecraft can maneuver in orbit safely.

All of this work represents a continuation of NRL's long tradition of research and development for space operations, which extends back to the creation of the Minitrack system and the launch of the Vanguard satellite, today the oldest manmade object in space.

Photo by NASA Orbital Debris Program Office

THE BIG DATA OF SPACE DEBRIS



U.S. Naval Research Laboratory Research physicist Liam Healy explains a model for a velocity distribution of fragmenting satellite debris. Photo by Emanuel Cavallaro

The U.S. Air Force maintains two operations centers that manage the satellite catalog (SATCAT), the catalog of 23,000 well-tracked objects in Earth orbit that includes both debris and controlled objects. One operations center resides at Vandenberg Air Force Base, California, and the other in Dahlgren, Virginia, at the site of the old Navy Space Surveillance Center; today it's the Air Force's Distributed Space Command and Control-Dahlgren.

For decades, NRL has worked with the operations center in Dahlgren, developing software products and advanced methods for space situational awareness (SSA). These days, researchers with NRL's Mathematics and Orbit Dynamics Section are helping the Air Force harness the potential of the ever-growing trove of private-sector SSA data collected by telescope networks and radars operated by universities, small startups, and other commercial entities.

"In the past, the government produced its own data using the Space Surveillance Network," said Christopher Binz, aerospace engineer with the Mathematics and Orbit Dynamics Section. "There was no concept of even a commercial provider of this data in the first place."

In recent years, this small industry has grown up around commercial SSA data, selling it mostly to the government but also to private companies. According to NRL research physicist Liam Healy, they're only now beginning to understand its value. Healy and other NRL researchers are helping to evaluate the industry itself, its sensor infrastructure, and the data it's producing for the Air Force's space acquisition agent, the Space and Missile Systems Center.

"I view it as being a consumer reports for the government purchaser," Healy said. "We need to evaluate what vendors have. But if it doesn't already exist, we need to do the research and development or sponsor the R&D to get to the point where we have a good idea of what we should purchase."

To do that, they're drawing on an asset that's unique to NRL: a complete database of the existing satellite catalog. According to Alan Segerman, who heads the Mathematics and Orbit Dynamics Section, the database is a product of NRL's long history of partnering with the operational community, compiled in fits and starts over a period of several years. It allows NRL researchers to test algorithms and run comparisons using the actual SATCAT data, rather than simulated data.

"Historically, we've developed a lot of the tools [used by the operational community], and from time to time we would get copies of the catalog," Segerman recalled. "Eventually, we were able to develop the infrastructure to collect the data as a copy of the operational archive every day."

At NRL's Space Situational Awareness Laboratory, they maintain the database of the operational catalog and Space Surveillance Network data in one server, and a database of the private sector data in another—just as is the case at the operations centers. Neither have integrated the two sets yet.

"We keep them separate, but we certainly have the ability to work with them together," Segerman said. "That's part of the analysis that we do."

An aerial view of the Air Force's space fence under construction on Kwajalein Atoll in the Marshall Islands. Photo by Lockheed Martin

A more recent area of their work today involves preparing for the completion of the Air Force's new "space fence" on Kwajalein Atoll in the Marshall Islands. A replacement for the Naval Space Surveillance System, space fence—which the Navy transferred to the Air Force in 2004—has been years in the making. It's forecast to become operational in 2019 and is expected to dramatically increase the number of objects we can track in orbit.

Right now, the Space Surveillance Network and the private sector can track objects in low Earth orbit that are approximately 10 centimeters in diameter and larger (the size limit of trackable objects grows larger the farther away you get from the Earth). A new fence, however, could reduce that size limit to single digits of centimeters.

The new fence also will use a mode of communication called netcentric data, rather than the Space Surveillance Network's current aging mode of communications, the 9600 BAUD modem, which was state of the art decades ago.

"The new space fence's data will still be radar observations, but it will come in a different form and contain more information than what the Air Force is used to processing," Segerman noted.

Segerman expects that when the new fence comes on line later this year, the number of warning messages of potential collisions will likely increase.

"Every time a better sensor like this new space fence is built, we can track smaller and smaller things," Segerman explained. "That means the tracked debris population increases—not because there's anything more up there, but because we're able to track more."

It's still unclear how the completion of the new fence will affect the nascent private sector industry, but no one thinks it will put private sensors out of business. Healy believes that, even though the new space fence will bring greater precision and increase the population of objects we can track, the Department of Defense will still need privately produced data.

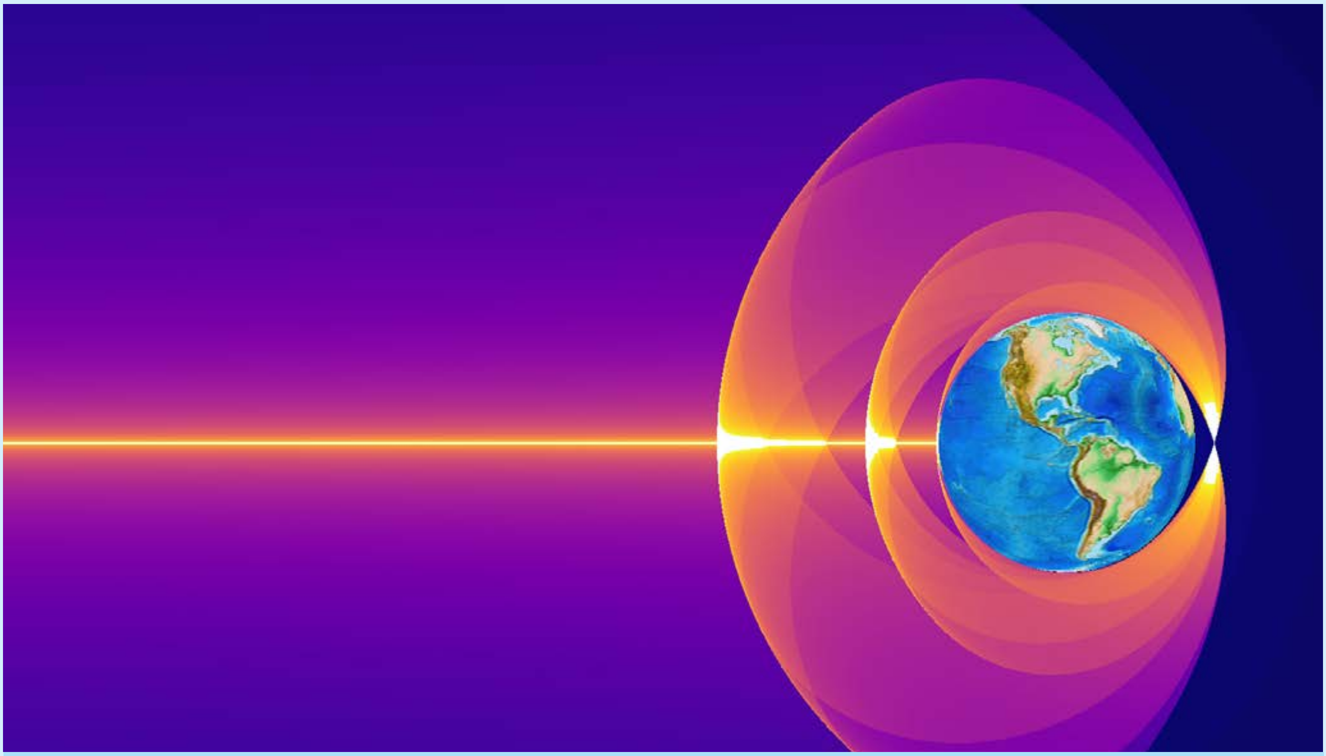
"There are some smaller objects that only the new space fence will be able to detect initially," he said. "We may recognize that we can use data from the commercial vendors to get more observations of these objects."

Binz speculates that the previously unknown smaller objects discovered by the new fence could push the industry away from using telescope networks and toward adopting radar technology to track them.

"There's just one company now doing commercial radar," Binz said. "More of those might pop up. Or companies might start building more powerful radars."

But the marshalling of private sector SSA data isn't just about observing objects we can't see, Segerman explains; it's also about increasing the frequency of observation of such objects, thereby freeing up government sensors to collect other data.

"The Air Force may have sensors that can already track these objects, but if we know the [private] vendor can provide good data on them, too, we can use our sensors to detect other objects that nobody else can," Segerman said. "And we can make that our priority instead."



Simulated space density of debris at five hours after fragmentation. Illustration by Liam Healy, Christopher Binz, and Scott Kindl

Here's How a Fragmenting Satellite Becomes a Debris Cloud

It's tempting to think of a collision or explosion in space the same way you imagine one happening on Earth, as a localized event occurring at a specific area. But when a satellite fragments in space, its pieces don't stick around. The satellite is in orbit, traveling at kilometers a second; when it breaks apart, each of its pieces will distribute according to the dynamics of the fragmentation and the satellite's orbit.

That's what Liam Healy and his fellow researchers Christopher Binz and Scott Kindl are attempting to understand with their ongoing project, begun in 2015. Before you can clean up debris from a fragmentation or collision in space, you have to know where the debris is, and where it's going. It turns out that's a complicated problem to solve, especially when you're dealing with fragments and particles too small to be detected and tracked from Earth.

In his research, Healy is considering the fragmentation of a satellite in terms of an initial velocity distribution, one that results in a spatial density of fragments that changes over time.

When an object explodes, the explosion adds velocity, and the velocities of the object's fragments have direction: forward, backward, left, right, up, or down. The velocities also have a magnitude. Some fragments travel at higher velocities, while others travel at lower velocities. All those fragments' velocities taken together as a set—that's a velocity distribution.

What Healy's team has done is model the fragmentation of an orbiting satellite by computing the evolution of the spatial density directly to simulate its velocity distribution. They've done that to study how the varying densities of debris distribute in space over time.

"If we know where those fragments are, we can follow those tracks, but often we can't, particularly the smaller fragments," Healy said. "For a long time, people have tried to understand the impact of debris on our orbital operations, and it's hard to get that understanding when you only have a bunch of tracks. The idea here is that if we simulate a distribution of those fragments, we can get at—basically—what a set of tracks that tell us where the fragments of the spacecraft are going as a whole."

In February 2016, Healy presented a paper on his team's work at an American Astronomical Society meeting along with a two-dimensional animated video showing how such a spatial density would look from the fragmentation of an object at 900 kilometers altitude over the course of 36 hours. Since then, his team has produced a series of colorful animations of the fragmentation of a spacecraft over time.

What the videos all show is a debris cloud spreading out from a single point where the fragmentation began (the "pinch point") and orbiting the Earth—with the brighter colors of the distribution indicating the areas of its highest density of fragments.

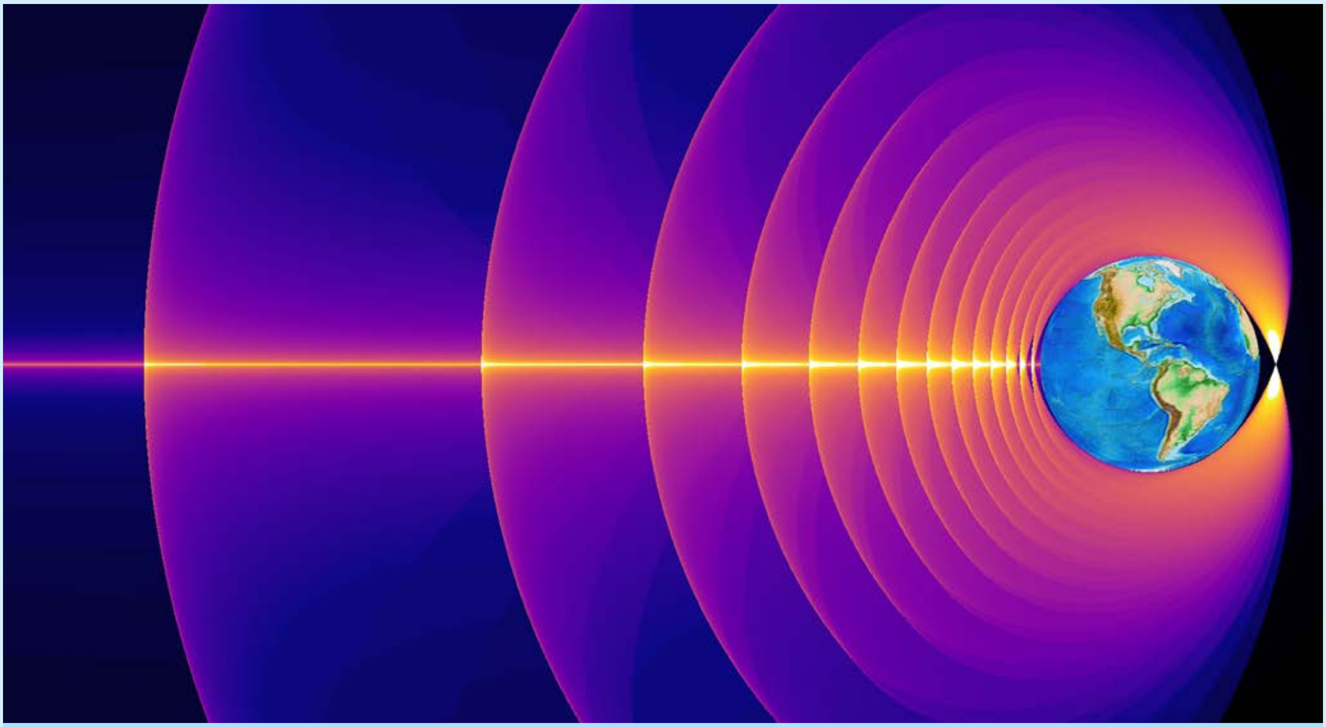
"What you see evolving in the simulation is the cloud spreads out from the pinch point, and this was already well known," Healy said. "But then there's going to be this band structure forming and this intense line of a high density region opposite the pinch point. No one had ever seen this pattern before."

The velocity distribution of a fragmentation event in orbit depends on the nature of the event. Is it an explosion? A collision? A disintegration? Each will have different velocity distributions. Regardless of the nature of the initial distribution, however, the line and band structure will look very similar, according to Healy. This is key, because that's where the distribution's greatest density of fragments will be.

"This is telling us this is where the hazard is from these kinds of events," Healy said.

Since the model describes how a distribution of velocities evolve from a single point, it can be applied to more than just the fragmentation of a satellite. The model deals with distributions, and a distribution can be an actual distribution of fragments, or it can be a virtual or probability distribution.

"Sometimes there's an object in space that's of interest, but we don't see it often enough to get a good orbit on it—so that is where this would also be applicable," Healy said. "If we have an uncertain orbit, say something that hasn't been observed very well, this tells us how the uncertainty grows as the orbit moves in time. The math is the same; the orbital physics is the same. And that's maybe of more interest to what we do, because this is a situation we face quite a bit."



Simulated space density of debris at 24 hours after fragmentation. Illustration by Liam Healy, Christopher Binz, and Scott Kindl

PROJECT LARADO

Andrew Nicholas, section head of the U.S. Naval Research Laboratory's Sensor Development and Applications, demonstrates the laser function of the Project LARADO demo. Photo by Emanuel Cavallaro.

Today, the Air Force's Space Surveillance Network has approximately 25 sites around the world with ground-based radars and optical sensors continuously collecting space situational awareness (SSA) data, which it makes available to the public online at Space-track.org. The network, however, is pumping out all the data it can—it's operating at capacity. And even with the completion of the new space fence, we still won't be able to see everything.

"There will still be the possibility that you'll be unable to detect something that could take out your spacecraft," Liam Healy said. "So then the question is: What's your known risk from tracked objects and what do you do about unknown risks? For the International Space Station, they took the approach of shielding for the smaller stuff."

Over the years, crew members on the International Space Station have even had to shelter in docked Soyuz capsules upon receiving word of passing debris that could potentially breach the station's shielding. The most recent incident occurred in March 2015, when astronauts learned only 90 minutes in advance of an approaching fragment from an old Russian satellite. The incident marked the fourth time in the station's history that astronauts had to seek shelter because of debris.

"This is likely a problem that will rapidly increase—especially since we're putting more and more satellites in orbit," said Chris Englert, who heads NRL's Geospace Science and Technology Branch. "The commercial sector is talking about putting thousands of satellites into Earth orbit in the not too distant future."

With Andrew Nicholas, section head of Sensor Development and Applications, Englert has been developing a method to detect orbital debris and micrometeoroids. Their project is called LARADO, for Light-sheet Anomaly Resolution and Debris Observation, and it's a space-based design concept for using satellite and laser technology to detect orbital debris in sizes that currently aren't detectable from the ground.

The idea is deceptively simple: Traveling on a satellite in orbit, LARADO aims a laser on an axicon, a specialized mirror with a conical surface, which distributes the laser's photons, creating a sheet of light in front of the satellite. Any object that passes through the sheet will scatter photons, creating a flash marking its passage that will be seen by a camera behind it with an ultrawide angle lens.

The device doesn't weigh much, and its scalability relies merely on the size of its camera and the power of its laser.

The more powerful the laser, the "wider" the sheet. On a satellite several meters long, a laser with the power of your average laser pointer would cast a sheet a couple of meters around the satellite, said Nicholas. The device should be capable of detecting debris at sizes as small as 0.01 centimeters—including debris that strikes the satellite.

Spotting debris in this way would have a number of applications, among them anomaly attribution—in other words, discovering what happened to your satellite. At low Earth orbit, objects that are too small to track are still traveling at orbital velocities of several kilometers a second. That means that, even though they're tiny, they pack enough kinetic energy to damage a multimillion-dollar satellite.

"What happens is that you fly a satellite and everything works great, and all of a sudden it doesn't, and no one knows why," Englert explained. "Objects in low Earth orbit are faster than a bullet coming out of a gun, so really small things can be pretty destructive."

With no way to detect tiny pieces of debris (smaller than about 10 centimeters in size) in low Earth orbit, satellite operators today have little way of knowing when such a piece has damaged a critical component of a satellite. Failed satellites are seldom recovered for analysis, and engineers and operators may attribute a failure caused by space debris to unrelated factors such as the satellite's design or parts.

Right now, a satellite operator might detect a collision when a piece of debris strikes the side of a satellite, changing its attitude or position. However, if a piece of debris passes through its center, or if a small piece of debris strikes a particularly large satellite, doing little to disturb its attitude, a damaging collision might go completely undetected.

"It's up there, so you can't take a look. You can't look at your electronics box and see there's a hole in it," Englert said. "But if you have something onboard that detects [the object] before it destroys something, you'll be able to say, 'Oh yeah, so we got hit by something.'"

With its potential for spotting tiny objects, LARADO might also be used to study the population density of space debris in low Earth orbit, capturing data on objects so tiny that even the new space fence won't be able to see them—objects like the many thousands of particles and fragments distributed by the Fungyun antisatellite test and the Iridium-Kosmos collision in 2009.

With the estimated number of objects orbiting the Earth smaller than one centimeter exceeding 100 million, Nicholas expects that when the new Space Fence comes on line there will still be a considerable gap in observation that LARADO would be able to capture data on. He envisions collecting data on the growing debris population by flying LARADO on host satellites over a range of altitudes (300 to 1,000 kilometers) over the period of a year.

"And if you want to really understand the density population of debris in low earth orbit, you might want a more powerful laser that makes a laser sheet that's tens or hundreds of meters across," Nicholas said.

Such data on previously undetectable space debris, he believes, would be a valuable source for the Space Surveillance Network as well as NASA's Orbital Debris Environmental Model, which NASA already updates regularly.

"You don't have to make a comprehensive measurement covering every square inch to make progress in that field, because there's so little data in that regime," Nicholas explained.

At this stage, Englert and Nicholas also are considering a number of design variations for LARADO. In one, the device would determine the direction of debris by projecting two sheets, one behind another, creating two parallel planes of light for the debris to cross. In another, LARADO would use a cone of light to sweep areas of space to detect nearby debris and other objects.

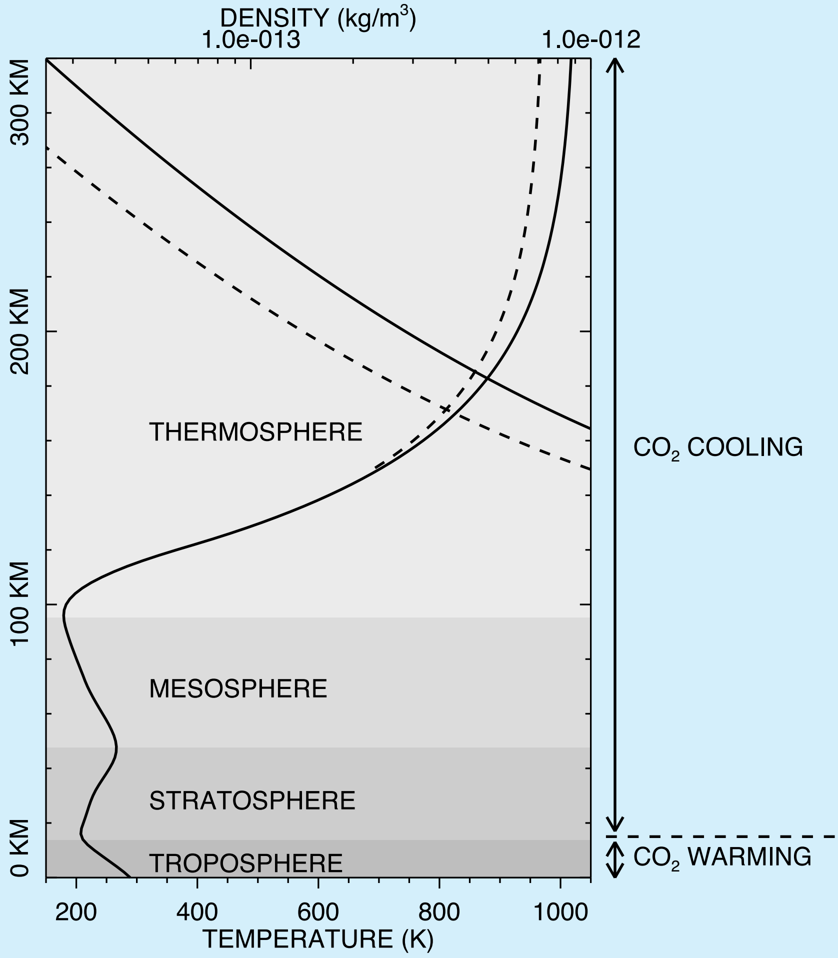
Nicholas believes that LARADO would pair well with NASA's own Space Debris Sensor (SDS), which uses resistive grids and acoustic signal information to distinguish the impact characteristics of different kinds of debris.

"You could do that exquisite [SDS] measurement that would give you the actual mass density and then fly a co-aligned version of LARADO," Nicholas said. "You'd get a really big area where you collect the population density on, then you'd get this smaller area where you get really exquisite data on the mass density as well. That would be very, very useful."

Since patenting the concept for the LARADO device in 2015, Nicholas and Englert have conducted preliminary lab tests with a number of everyday objects—marbles, erasers, pens. For further testing and, ultimately, the construction of a space-qualified unit, they plan to partner with a sponsor such as the Air Force or NASA's Orbital Debris program office.

They are proposing more sophisticated tests of a demo of the device with high speed objects, such as testing at the NASA Ames Vertical Gun Range, a facility that can simulate high-speed impacts by firing projectiles at orbital velocities up to seven kilometers a second.

HERE'S WHAT ORBITAL DEBRIS CAN TELL US ABOUT EARTH'S CHANGING ATMOSPHERE



This graphic illustrates the effect of the doubling of CO_2 on the temperature and density of the upper atmosphere. The curving solid line beginning at the bottom and curving to the right shows temperature, which increases significantly as it approaches the thermosphere. The dashed line splitting off it shows the reduction in temperature in the upper atmosphere that may result from the doubling of CO_2 in the atmosphere. The other pair of lines at the top indicate the density of the atmosphere, with the dashed line showing the decrease in density with CO_2 doubling. This illustration is based on the 1989 study by Ray Roble and Robert Dickinson that predicted a doubling of CO_2 (from 330 parts per million to 660 ppm) would reduce thermospheric temperature by 50 Kelvin. Graphic by John Emmert

John Emmert first got involved in studying orbital debris while studying climate change in the upper atmosphere. For the purposes of his research, the pieces of debris in low Earth orbit are less a problem than an opportunity. To him, they're a collection of atmospheric probes.

Emmert, a research physicist with NRL's Space Science Division, has been using tracking observations of changes in their orbits to infer the density of the atmosphere. He has been studying the long-term trends and the density derived from the orbital debris tracking observations in the Space Surveillance Network data since he first joined NRL 15 years ago as a National Research Council postdoctoral fellow.

What he's found is that increasing levels of carbon dioxide are exerting a gradual but dramatic effect on the upper atmosphere. More carbon dioxide in the atmosphere is causing the atmosphere to contract, he says. That's because, while the atmosphere nearest the Earth's surface is warming because of climate change, the atmosphere above the troposphere is cooling.

"The day-to-day orbital changes tell you how much [atmospheric] density the orbital debris went through, and that density seems to be going down relative to what we expected it to do," Emmert said.

According to a 2004 study conducted by Emmert and fellow NRL researchers, which corroborates the work of European and American researchers, the atmosphere about 400 kilometers above the Earth is thinning by two percent a decade. If carbon dioxide levels double as projected, the density at this altitude could decrease by as much as 50 percent by the end of the century.

Above the troposphere, carbon dioxide is a major cooling source, the main way the upper atmosphere sheds its energy from the sun, Emmert said. Acting as a cooling agent, increasing levels of carbon dioxide are tipping the balance toward colder temperatures, lowering the density of the upper layers of the atmosphere that normally produce drag on the 15,000 or so objects in low Earth orbit.

And that means that orbital debris—between 80 and 2,000 kilometers above the Earth—could stay in orbit even longer than it otherwise would, while future space operations ensure that more and more of it continues to accumulate.

"Think of this as of long-term interest to the space debris problem," Emmert said. "Satellites that are still active can change their trajectory to reenter on their own. But once something's dead up there, there's nothing to cause it to deorbit except atmospheric drag. What's going to happen to the amount of debris in the future? One possibility is that, because the drag is less, it slows the reentry process of debris, so less of it reenters the atmosphere as a result."

During a recent project, which Emmert named Presage, he worked with Alan Segerman, head of NRL's Mathematics and Orbit Dynamics Section, to characterize atmospheric density as a source of uncertainty in tracking objects in space. When it comes to orbit determination, knowing the uncertainty is almost as important as knowing where the object is going to be, Emmert said.

"There is always uncertainty, especially when you have so many thousands of objects," he said. "Understanding that uncertainty of where these things are is a big issue called 'covariance realism' that's now recognized in the community—making sure we have an accurate estimation of the error, which sounds oxymoronic."

Emmert calls atmospheric density the biggest source of error when it comes to predicting where an object in low Earth orbit will travel over the timespan of three to seven days, the window during which satellite operators generally want to know whether another object has the potential to enter the path of an operational satellite.

As part of the project, which wrapped up in September 2017, Emmert and Segerman produced a model predicting varying levels of uncertainty that takes into account not just atmospheric density but also solar activity, which varies day to day as well as according to an 11-year sunspot cycle.

During solar maximum (the period of greatest solar activity during this cycle) solar energy causes the Earth's thermosphere to expand, which causes additional drag on debris in low-Earth orbit, deorbiting some of it. The sun is currently headed toward solar minimum, its period of least activity.

"The solar part [of the research] was a major part of it, because a lot of the uncertainty of the density is coming from our not being able to predict what the sun is going to do," Emmert said. "We wanted to have a quick way to say, if this is your given density uncertainty, this will be what you can expect your position uncertainty for a given debris object or satellite. And we came up with a way to do that. It's actually a very interesting mathematical problem."

According to Emmert, neglecting to account for these factors of atmospheric density and solar activity when performing orbit determination can lead to levels of uncertainty that are unrealistically small.

"So if you think your uncertainty is smaller than it is—if you're handling the atmospheric uncertainties in sort of an ad-hoc way—you might think that something is not a threat and have a false negative of your assessment of the threat," he said.

"Astrodynamicists who are working for NASA or DoD and just navigating their spacecraft through all this debris—they know this."

OCEAN

WE HIT GO—AND IT WORKS

Photo by Emanuel Cavallaro

In space, fuel is life. Though NASA and NRL are researching options for servicing and refueling satellites, satellites currently aren't refueled—ever. The fuel a satellite takes into space is all the fuel it will ever have. So anytime a satellite has to maneuver, whether it's to adjust its orbit or evade collision with space debris, its lifespan shortens..

No one knows this better than Joshua Brooks, who heads NRL's Blossom Point Tracking Facility, which today is actively flying five satellites, among them WindSat, Upper Stage (MITEx), and eXCITe, a satellite for DARPA that launched in December 2018. Managing operations for multiple satellites at Blossom Point once involved crews of operators manning terminals on shifts, 24 hours a day, seven days a week. Today, nearly all of that is automated, managed by a handful of operators.

That is thanks in part to NRL's high-precision, orbit-determination software suite called OCEAN (for Orbit/Covariance Estimation and Analysis). Brooks, who began his space operations career with the Air Force as a ground radar operator doing space object monitoring, credits OCEAN as a huge contributor to the facility's evolution.

The software suite is a space operations project that NRL has been running for more than two decades. One of the first programs to use it was NRL's 1994 Deep Space Program Science Experiment mission to map the moon (better known as Clementine).

"OCEAN is so much better than the orbit-determination tools that I was using in the Air Force," Brooks said. "If we had been using OCEAN, or if the Joint Space Operations Center, who used to do the traffic management function, had used OCEAN as the system of record for orbital analysis there would have been a lot fewer collision avoidance warnings and potential maneuvers."

Aerospace engineers Evan Ward and Greg Carbott aren't based at Blossom Point, but as OCEAN's main developers with NRL's Astrodynamics and Navigation Section, they visit the facility fairly regularly. Achieving a high-precision orbit, they will tell you, means reducing the uncertainty around a spacecraft and the uncertainty around the objects around it.

Think of the area of uncertainty around an object as a bubble. Should a satellite's bubble of uncertainty threaten to pass through the bubble of uncertainty around a debris cloud, the satellite will have to maneuver out of the way, expending its limited fuel in the process, or risk being damaged by a collision.

"If you have a small bubble, you don't have to maneuver," Ward said. "You can say for sure that debris won't hit my satellite because you've reduced the area where you know where the debris is. That's where most of our efforts have been focused on, producing high-quality orbit determination and ephemeris products for operational satellites. We can produce better knowledge of where our own satellites are and where the debris is, which means that you don't have to use as much fuel to maneuver your satellite to avoid a collision, and that you have a longer life for your satellite."

Using data from GPS, the Air Force Satellite Control Network, and other sources, OCEAN determines where a spacecraft is located in space and there it will be located in the future. Here's how it works: When the ground antennas at Blossom Point initiate contact with a spacecraft with a radio signal, the satellite retransmits the signal, and Blossom Point begins receiving telemetry data. That data flows onto the computer systems and into OCEAN, which calculates the time it took for the signal to reach the satellite and return, using that information paired with the angle of the antenna to determine where the satellite is located in the sky.

"That gives us a pass overhead, and then we can use that to fit an orbit to it," Ward said. "Typically, we get multiple passes to produce an orbit. And then we use that orbit to predict where the satellite's going to be in the future, so we know where to point the antennas for the next pass."

OCEAN then provides the ephemeris (the predicted position for the spacecraft) to the Joint Force Space Component Command (JFSCC), the Air Force operational arm for satellite

U.S. Naval Research Laboratory aerospace engineers Evan Ward (left) and Greg Carbott (right). Photo by Emanuel Cavallaro

command and control. JFSCC compares that position to the objects in its catalog. If a maneuver is necessary to avoid a potential collision, OCEAN uses that position data to calculate a maneuver plan for the spacecraft.

"When JFSCC thinks you're getting too close to another operational satellite or piece of space debris, they'll send what's called an 'orbital conjunction message,'" Ward explained. "'Conjunction' is just another technical term that means you're getting close to something."

"We would then produce a maneuver plan, and provide that to the [satellite's] operators, who would then command the satellite to perform that maneuver," Carbott said.

Orchestrating the whole process is Neptune, NRL's multimission command-and-control software, which handles all the communication with the spacecraft antennas and the command of the spacecraft. Neptune and OCEAN are both "lights out"—fully automated—which means that much of the time this extremely complex process unfolds without the assistance of a human being.

"You have some preconfiguration that you need to do, and there's some hiccups that can happen," Carbott said. "But for nominal operations we configure it, we hit go, and it works."

As engineers, Ward and Carbott's role consists of working to advance the heritage software, continually improving OCEAN's reliability, precision, and accuracy, as well as configuring the software for new missions, each of which come with its own set of unique demands. When the new space fence comes on line and begins pumping out higher-quality data, they may also have to update the software.

When it comes to orbital debris, however, though these operations are in place to ensure precise and safe maneuvers to avoid it, Ward and Carbott have not yet experienced any issues. Neither has Brooks. Partly, that's because right now some of their satellites fly in the subsynchronous orbital regime, where space debris is relatively uncommon.

Their others satellites—such as WindSat—fly in the polar orbital regime. That's where the Fengyun antisatellite missile test occurred, inserting most of that debris into polar orbit. According to Ward, WindSat flies a similar orbit, placing it at relatively high risk of collision with Fengyun debris. So far, though, WindSat hasn't encountered any of it.

"I agree that [orbital debris] is a good thing to focus on," Ward said. "My position is that at the moment it's not a big issue for us, but we need to pay attention to make sure it doesn't become one."

In 2011, the National Research Council (NRC) released a report outlining findings from its study of NASA's meteoroid and orbital debris programs. In it, the NRC warned that debris from Iridium-Cosmos collision and the Fengyun event may have already pushed the orbital debris environment toward a tipping point where the cascading collisions predicted by Donald Kessler had already begun.

The report nonetheless noted the measures the operational community has taken over the previous 50 years to protect critical components of spacecraft and mitigate the generation of new debris: satellites redesigned, orbits monitored, and new protective shielding added to the International Space Station.

Indeed, studies by NASA's Orbital Debris program have led to US policies and international agreements limiting the net growth of debris in low Earth orbit—policies that order the venting of propellant tanks to prevent them from exploding (tank explosions were one of the earliest causes of orbital debris) or deorbiting defunct satellites to burn up in the Earth's atmosphere or enter a graveyard orbit.

As NRL's work continues, we can take solace that today, eight years after the release of NRC's report, the accumulation of orbital debris remains a manageable problem that we still have time to solve. For their part, Ward and Carbott are consoled by one indisputable fact of space operations.

"Space is big," Ward said.

There's a lot of room up there. For now.

About the author:

Emanuel Cavallero is a writer with the U.S. Naval Research Laboratory.

73 YEARS IN SPACE

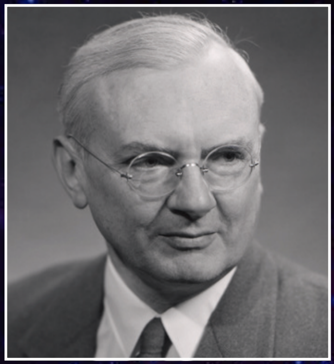
The U.S. Naval Research Laboratory (NRL) entered the realm of space soon after American forces entered Germany in 1945 and captured the huge underground factory for V-2 rocket production at Nordhausen. The Americans confiscated about 100 rockets and shipped them to the White Sands Missile Range in New Mexico, where the Army set about studying the propulsion system. The first American-launched V-2 flew from White Sands on 16 April 1946.

Seeing the opportunities for upper atmosphere research and solar astronomy, NRL took the lead in the Navy for conducting rocket research. The V-2 Rocket Panel was formed with membership from NRL, the Applied Physics Laboratory at Johns Hopkins University, the California Institute of Technology, Harvard University, the University of Michigan, and other organizations to oversee the allocation of space on V-2 rockets for high-altitude research, with NRL's Ernst Krause as the first chair. The research goals included radio and sound propagation in the atmosphere, properties of the atmosphere, cosmic rays, solar ultraviolet radiation, and various biological investigations.

NRL's V-2 experiments in 1946 and 1949 marked the beginning of a major space science program at the lab. Within a decade, NRL developed a foundation of rocket science that formed into two distinct branches: one related to applications (including the development of scientific payloads) and the other devoted to the development of rocket technology.

This timeline highlights some milestones in NRL's space program as it developed from those postwar years to the present.

1946

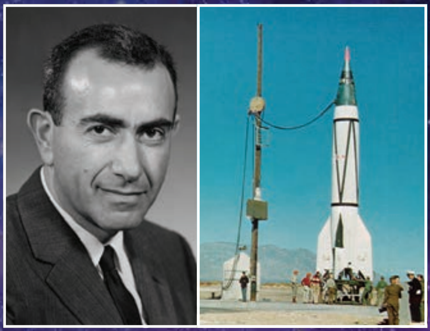


Richard Tousey's first V-2 rocket flight measured solar ultraviolet radiation.

1949

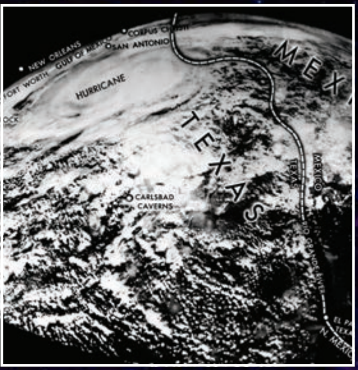
First flight of NRL's Viking rocket, designed to replace the V-2 for scientific missions that required higher altitudes and pointing stability.

1949



Herbert Friedman's first V-2 rocket flight measured solar X-radiation. Friedman later made the first positive identification of stellar X-rays in 1963.

1954



1954 NRL's photograph of a hurricane from an Aerobee rocket was the first time a major weather feature was seen from space, and a convincing argument that space cloud imagery could be a valuable tool for meteorologists.

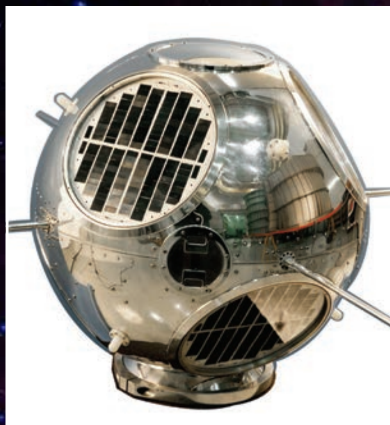
1958

Vanguard I, the oldest man-made satellite still in orbit, launched on St. Patrick's Day.

NRL conducted Project Vanguard for the International Geophysical Year of 1957-1958. NRL designed and developed the three-stage rocket, the grapefruit-sized satellite, and the Minitrack network that tracked the satellite using radio interferometry. The Vanguard team was transferred in October 1958 to the new National Aeronautics and Space Administration (NASA).

Extending the Minitrack concept, NRL developed the Naval Space Surveillance System (NAVSPASUR) over the next six years.

1960



Launch of GRAB, the first U.S. "spy" satellite, along with SOLRAD payload, which monitored solar X-radiation.

The month after a U-2 aircraft was lost on a reconnaissance mission over Soviet territory, GRAB I was launched and began transponding intercepted electronic intelligence signals to ground stations. GRAB demonstrated the value and viability of space-based intelligence platforms. The SOLRAD series of satellites studied the Sun's effects on Earth on missions from 1960 to 1979.

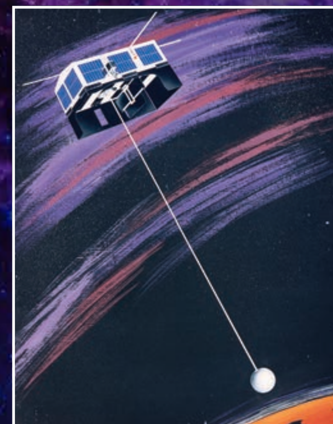
1961

First launch of the Low Frequency Trans-Ionospheric (LOFTI) radio satellite to study the propagation of radio waves through the ionosphere.

1965

Launch of OSO-2, the first in a series of Orbiting Solar Observatory missions for which NRL developed solar physics instrumentation.

1967



Launch of the first of four Timation (time and navigation) satellites, which demonstrated NRL's new navigation concept that became GPS. Followed by Timation II (1969), Timation IIIA/Navigation Technology Satellite (NTS)-1 (1974), and Timation IV/NTS-2 (1977).

1971

First observation of a coronal mass ejection (CME) from space, by an NRL coronagraph on board OSO-7.

1972

NRL's Lunar Surface Camera operated on the Moon during the Apollo 16 mission, obtaining images of the Earth and celestial objects.

1973

NRL solar spectrometers operated on Skylab, America's first space station.

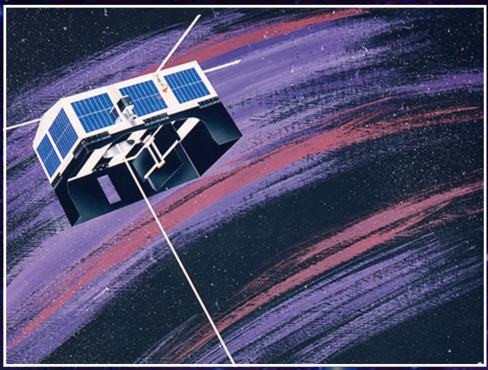
1976

First launch of the Multiple Satellite Dispenser, an upper stage for the Atlas F booster, which carried multiple satellites into precise orbits.

1979

Launch of the SolWind Coronagraph on a DoD satellite to monitor the solar corona and catalog CMEs. First observation of a CME headed toward Earth, a so-called halo CME.

1982



The first of five Space Shuttle flights of NRL's Solar Ultraviolet Spectral Irradiance Monitor (SUSIM) which measured absolute solar ultraviolet irradiance and examined the impact of solar variability on the Earth's ionosphere and climate. SUSIM also flew on the Upper Atmosphere Research Satellite (1991–2005) and produced the longest continuous absolute measurement of solar ultraviolet irradiance to date.

1983

Launch of Living Plume Shield (LIPS) II to demonstrate direct downlink of tactical data from a low-Earth orbiting spacecraft.

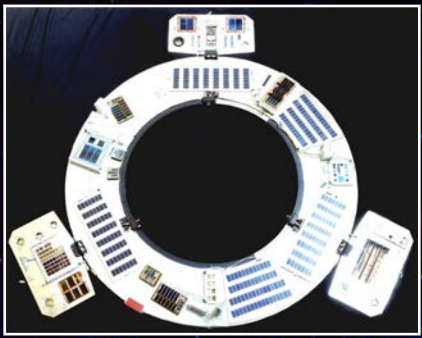
1985

NRL scientist Dr. John Bartoe flew on the Space Shuttle as payload specialist for NRL's High-Resolution Telescope and Spectrograph, which recorded ultraviolet spectra of the Sun.

1987

The first Special Sensor Microwave Imager (SSM/I) was flown in DoD's Defense Meteorological Satellite program to map water vapor and ocean wind speed. NRL pioneered this technique.

1987

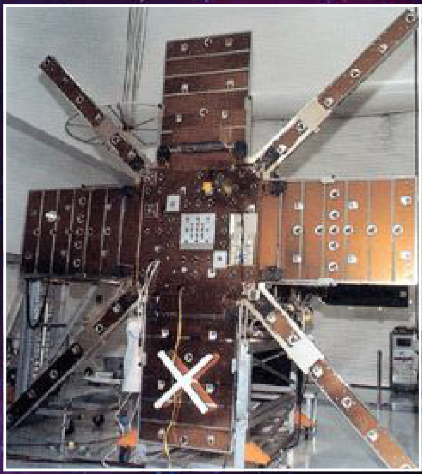


Launch of LIPS III provided a test bed for new space power sources.

1990

NASA's Compton Gamma Ray Observatory containing NRL's Oriented Scintillation Spectrometer Experiment was put in orbit from the Space Shuttle. It operated for 10 years.

1990



Launch of the Low-Power Atmospheric Compensation Experiment, a spaceborne target with sensors to characterize a laser beam emitted from a ground-based laser site.

1991

Launch of the Japanese Yohkoh solar observatory with NRL instrumentation on board to measure high-energy solar phenomena. Yohkoh provided the first definitive observations connecting solar flares to the breaking and reconnection of magnetic fields.

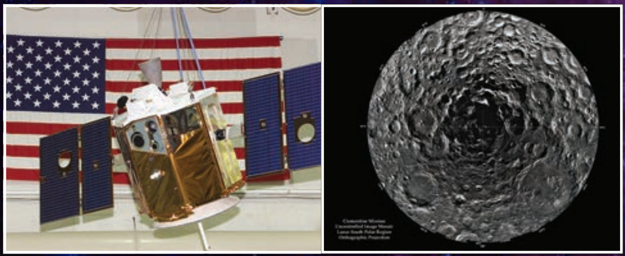
1993

NRL's Polar Ozone and Aerosol Measurement instrument was launched on the French Space Agency SPOT remote sensing satellite.

1994

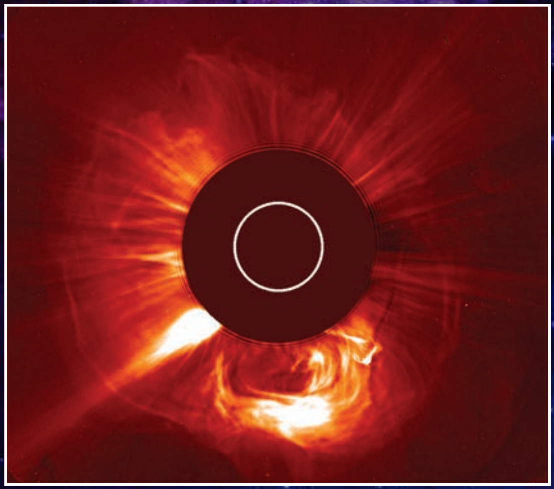
First flight of NRL's Middle Atmosphere High-Resolution Spectrometer Instrument on the German Space Agency's Shuttle Pallet Atmosphere satellite, to make global measurements of hydroxide in the mesosphere and upper stratosphere.

1994



The DoD-NASA Clementine satellite, developed by NRL under the mantra of "faster, better, cheaper," was launched to test lightweight miniature sensors and advanced spacecraft components, and to map the entire lunar surface.

1995

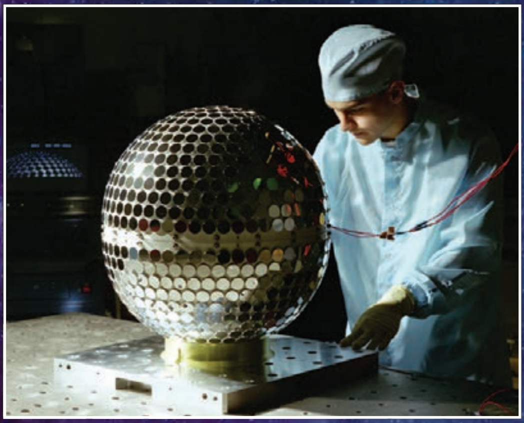


NRL's Large Angle and Spectrometric Coronagraph and Extreme Ultraviolet Imaging Telescope launched on the European Space Agency/NASA Solar and Heliospheric Observatory. These instruments help to understand the mechanisms that form CMEs and drive the solar wind, providing a genuine basis for predicting geomagnetic storms on Earth.

1999

The ARGOS satellite contained five NRL instruments to measure the upper atmosphere, conduct astronomy experiments, and test new technology.

1999

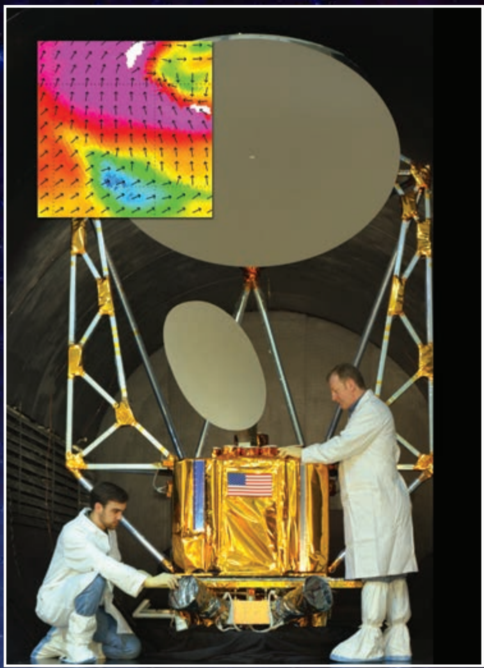


First launch in Project Starshine, a science-education project for measuring variations in the density of Earth's upper atmosphere during solar storms. Students from all over the world helped to build the satellites and collected data from them.

2003

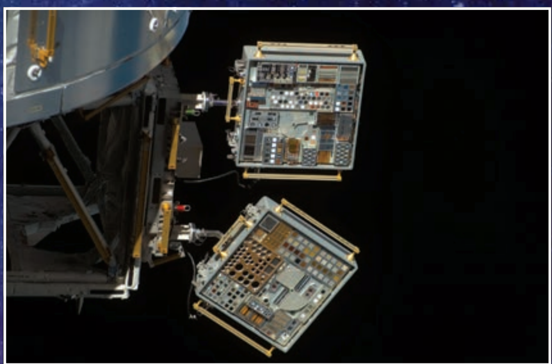
The first in a series of NRL's Special Sensor Ultraviolet Limb Imagers flew on a Defense Meterological Satellite Program satellite, providing operational environmental data for warfighters.

2003



WindSat, the first spaceborne polarimetric microwave radiometer, launched on the NOAA/DoD/NASA Coriolis spacecraft to measure wind speed and direction at the ocean surface.

2005

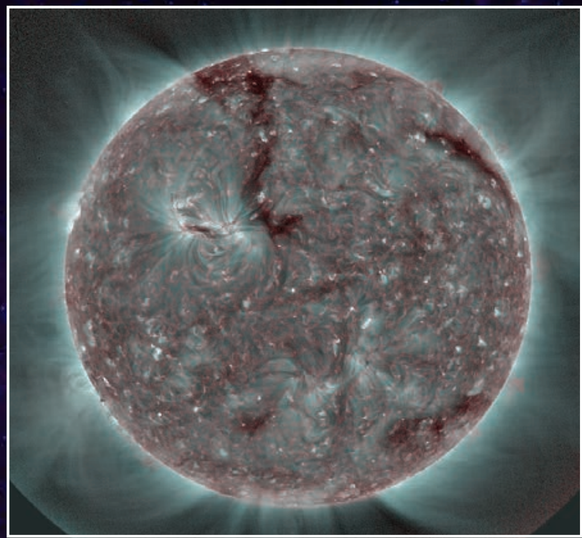


MISSE-5 launched to the International Space Station. The suitcase-sized experiment exposed hundreds of samples of materials and components to the harsh space environment for later analysis of the effects. Followed by MISSE-6 (2008), MISSE-7 (2009), and MISSE-8 (2011).

2006

Launch of TacSat-2, part of the Operationally Responsive Space initiative to bring tactical capability to warfighters rapidly, without the decade of development normally associated with operational military satellites.

2006



Launch of NASA's Solar Terrestrial Relations Observatory. NRL's Sun-Earth Connection Coronal and Heliospheric Investigation telescopes provide three-dimensional observations of CMEs as they form at the Sun and traverse interplanetary space to Earth.

2006

Atmospheric Neutral Density Experiment (ANDE) microsatellites deployed to monitor atmospheric density for improved orbit determination of space objects. ANDE-2 was launched in 2009.

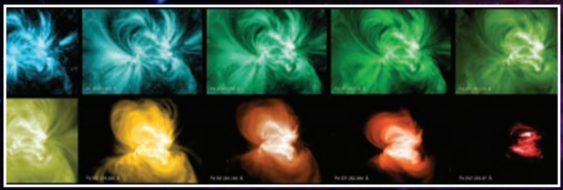
2006

Launch of the Taiwan-U.S. COSMIC/FORMOSAT3 mission with NRL's Tiny Ionospheric Photometer compact, far-ultraviolet sensors on board to study Earth's night-side ionosphere.

2006

Launch of the Microsatellite Technology Experiment, with NRL's Upper Stage, to test and evaluate small satellite technologies.

2006

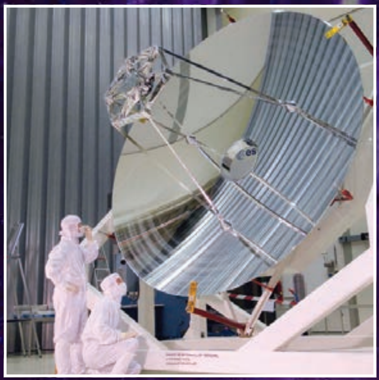


Launch of the Japanese Hinode solar observatory with NRL's Extreme-ultraviolet Imaging Spectrometer to measure temperature, density, and dynamics of the solar corona.

2007

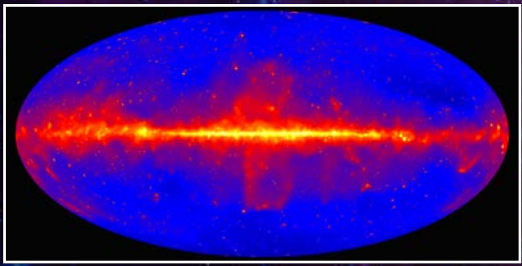
Launch of STPSat-1 carrying SHIMMER and CITRIS. SHIMMER measured hydroxyl in the middle atmosphere, and demonstrated spatial heterodyne spectroscopy for space-based remote sensing. CITRIS detected when and where scintillation and refraction adversely affect radio propagation, and provided global maps of ionospheric densities.

2008



Launch of the European Space Agency Herschel Space Observatory that measures terahertz radiation from astronomical and planetary objects. NRL contributed to the optical system of the 3.5-meter-diameter, silicon carbide Cassegrain telescope.

2008



Launch of the Fermi Gamma-ray Space Telescope to survey the high-energy space environment. NRL led the team that designed and manufactured the Large Area Telescope calorimeter, which measures the energies of gamma rays from astronomical objects and the Sun.

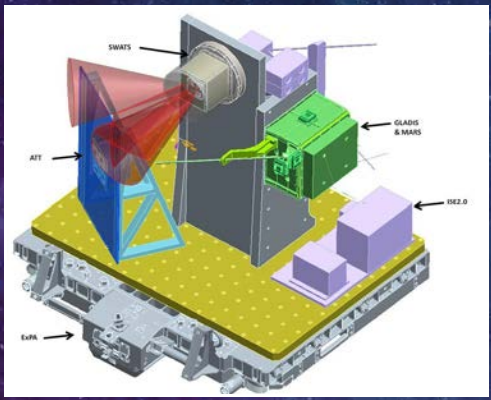
2009

HICO/RAIDS launched to the International Space Station. The Hyperspectral Imager for the Coastal Ocean and Remote Atmospheric and Ionospheric Detection System collect useful environmental data for military and civilian systems.

2011

Launch of TacSat-4 with its COMMx payload to support communications-on-the-move, data exfiltration, and blue force tracking. It is designed to be reallocated rapidly to different theaters worldwide.

2013



Launch of several of NRL's space science and technology experiments on NASA's Space Test Program/Houston-4 mission. Among them were the Small Wind and Temperature Spectrometer and Global Awareness Data-Exfiltration International Satellite.

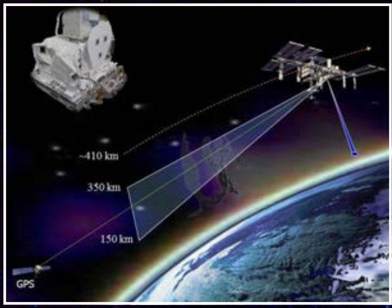
2014

Launch of SpinSat to the International Space Station aboard a SpaceX Falcon 9 resupply mission. Astronauts aboard the International Space Station later successfully deployed NRL's SpinSat into orbit. SpinSat was a small, spherical satellite designed to demonstrate new thruster technology, calibrate the space surveillance network, and model the density of the atmosphere.

2015

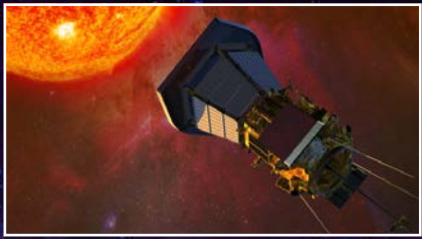
Launch of the Charged Aerosol Release Experiment, an instrumented rocket launched in collaboration with universities and government laboratories. The launch, which was designed to study the effects of dusty plasmas, charged dust particles that can occur naturally in the mesosphere, generated an artificial plasma cloud in the upper atmosphere.

2017



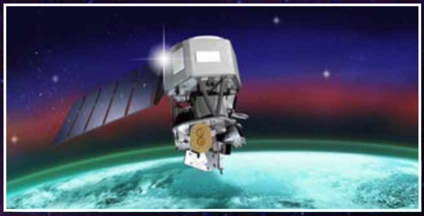
Launch of two experiments on the SpaceX Falcon 9 rocket to the International Space Station. The experiments were the Limb-Imaging Ionospheric and Thermospheric Extreme Ultraviolet Spectrograph, and the Global Positioning System Radio Occultation and Ultraviolet Photometer Co-located. Together they formed a suite of high performance sensors that produced two- and three-dimensional maps that display multiscale plasma structures found in the ionosphere.

2018



Launch of NRL's Wide-Field Imager for Solar Probe (WISPR) instrument on the NASA's Parker Solar Probe, a revolutionary mission to go deep in the heart of the sun's corona. WISPR was designed to analyze evolving solar wind structures close to the Sun and derive the three-dimensional structure of the solar corona to determine the sources of the solar wind.

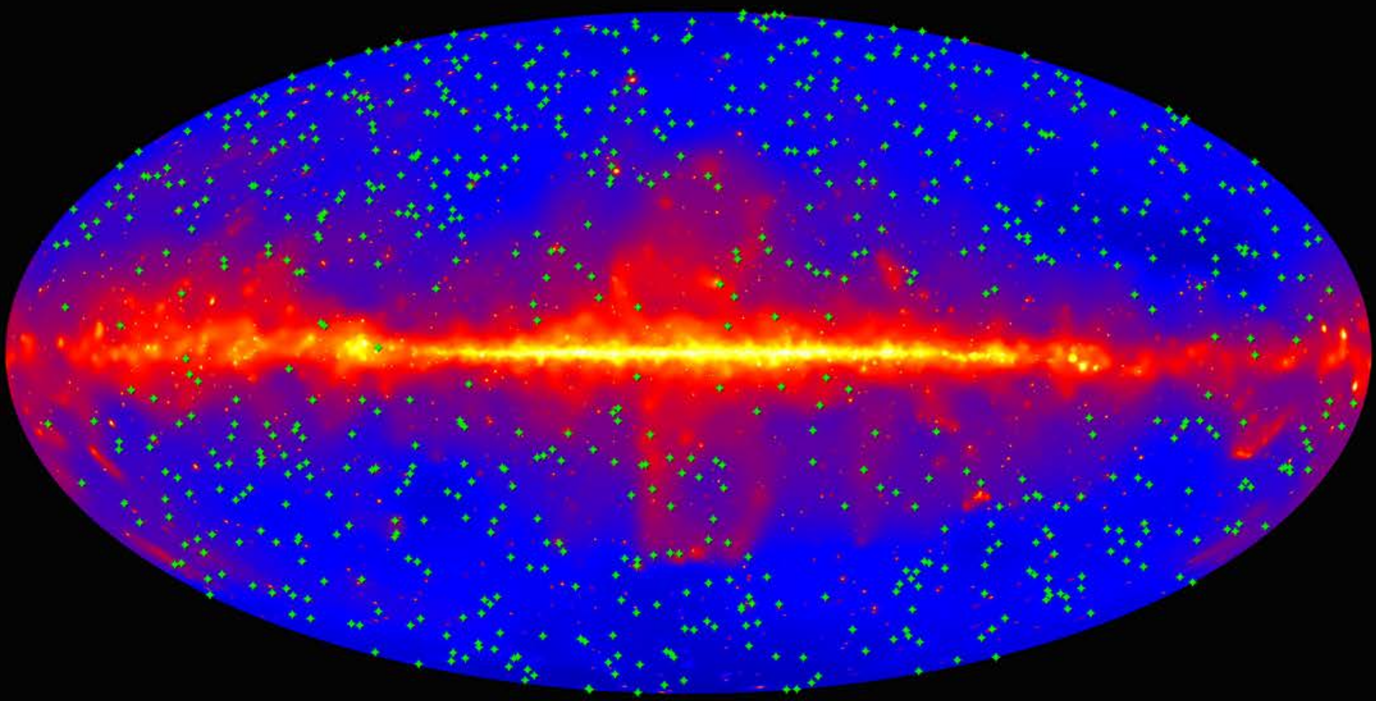
2019



Launch expected for NRL's Michelson Interferometer for Global High-resolution Thermospheric Imaging (MIGHTI) satellite instrument as part of NASA's Ionospheric Connection Explorer (ICON) mission. MIGHTI is part of a suite of instruments on ICON designed to determine the conditions in space modified by weather on Earth and to analyze the way space weather events develop. MIGHTI is designed to measure the neutral winds and temperatures in the Earth's low-latitude thermosphere.

FERMI TELESCOPE
MAPS THE HISTORY OF STAR FORMATION

By Gabrielle M. Gibert



THE FERMI GAMMY-RAY SPACE TELESCOPE, LAUNCHED IN 2008, SEARCHES THROUGH THE FARTHEST REACHES OF SPACE FOR THE ORIGINS OF HOW STARS ARE FORMED.

Researchers from the Fermi Gamma-ray Space Telescope Collaboration, including scientists at the U.S. Naval Research Laboratory (NRL), used Fermi to measure the rate of star formation through interactions of gamma rays with extragalactic background light, gaining insight into the star formation history of the universe. Research findings were published in the 29 November 2018 issue of *Science*.

The universe is 13.8 billion years old, with stars being born, living, and dying for most of that time. The stars create a relic light that fills the universe, known as the extragalactic background light, or EBL. The EBL is made up of light from all the stars that have ever lived in the observable universe, even long after they have ceased to shine.

In 2010, Dr. Justin Finke of NRL's High Energy Space Environment Branch was part of a team of NRL

(Previous Page) Image of the sky at gamma-ray energies from the Fermi Space Telescope, with green points indicating 739 blazers. Image by NASA/DOE/Fermi LAT Collaboration

researchers that created a model for EBL. This model and a similar model created by collaborator Dr. Kari Helgason of the Max Planck Institute for Astrophysics (now at the University of Iceland) were used to convert the EBL measurement into a measurement of star formation history. The results using both models are similar, increasing confidence in the measurement.

Using these results, the scientists were able to measure how many stars were formed over most of cosmic history.

The key to measuring EBL is through "blazars," according to Finke.

"Blazars are super-massive black holes that generate gamma rays," Finke said. "These gamma rays interact with background light from stars that converts the gamma rays into pairs of particles."

Gamma rays are the most energetic form of light. Each individual gamma-ray photon, or particle of light, seen by Fermi has energy billions of times more than the photons seen with the human eye.

"By determining how many gamma rays are missing from our observations and how many get transformed by interacting with starlight, we can measure how much of the starlight there is," Finke said.

This process was done for a very large blazar sample, spread out over many different distances. Fermi's Large Area Telescope is especially suited to measuring the blazars' gamma rays and interactions with EBL.

"There is nothing else that can measure gamma rays like Fermi can in this energy range," Finke said of the telescope's capabilities.

This was the first measurement of star formation history with gamma rays over such a large range of cosmic time. The recent measurement also was able to constrain the formation of the first stars in the universe, opening the door for future research projects, according to Finke.

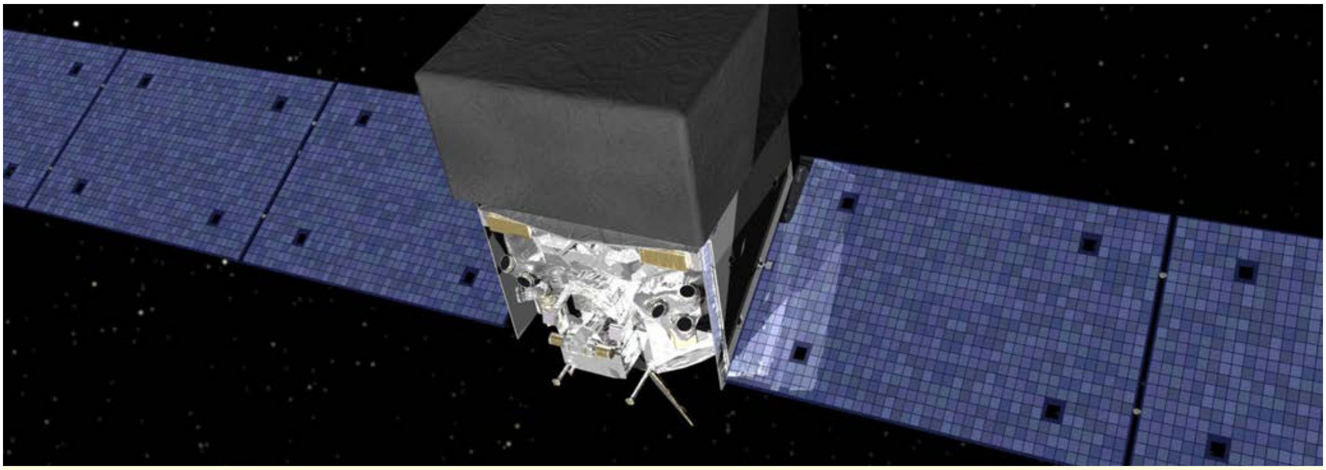
"The first stars formed in the very early universe were thought to re-ionize the universe, making the hydrogen in the universe go from mostly neutral to being mostly ionized," Finke said. "Understanding that process is a major goal of the upcoming mission for NASA's James Webb Space Telescope."

The study shows that mapping the history of the stars helps space scientists from NRL and other institutions learn more about the universe's past, while providing valuable information for space exploration in the future.

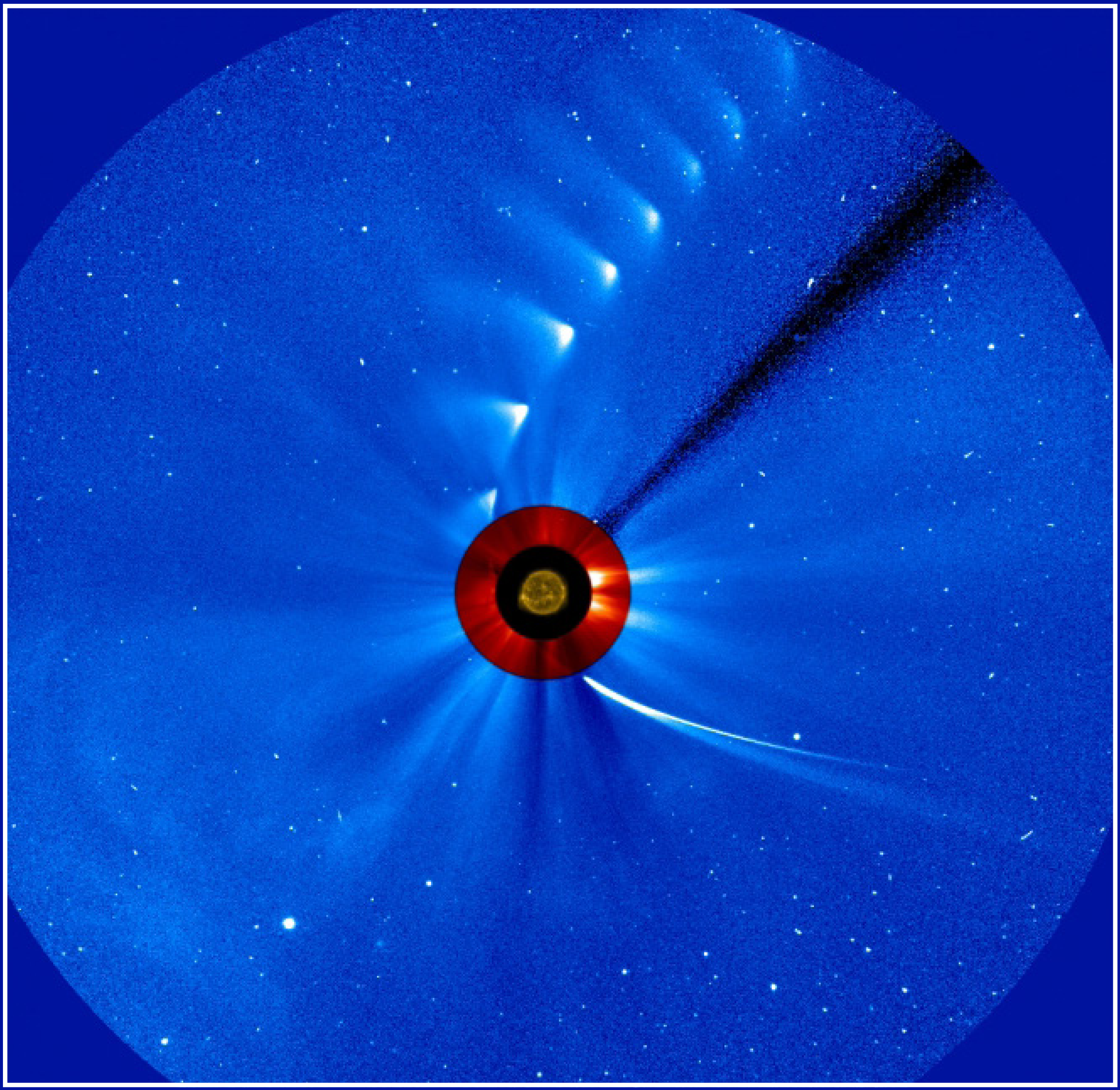
NRL's Space Science Division was one of the principal developers of the Fermi Large Area Telescope instrument. Fermi is supported by NASA and the Department of Energy, with important contributions from institutions in France, Germany, Italy, Japan, and Sweden. The current research was led by Marco Ajello, Vadehi Paliya, and Abeshik Desai at Clemson University; Alberto Dominguez at the Universidad Complutense de Madrid in Spain; Kari Helgason at the University of Iceland; and Finke at NRL.

About the author:

Gabrielle Gibert is a writer with the U.S. Naval Research Laboratory.



Artist's concept of Fermi Gamma-ray Space Telescope. Image by NASA



SUNGRAZER AT 15

HOW CROWD SOURCING CHANGED COMET HUNTING

By Sara Francis

SPACE OBSERVATION ISN'T JUST FOR CLOISTERED SCIENTISTS IN LABORATORIES. THE SUNGRAZER PROJECT HAS MADE SEARCHING FOR COMETS--SHOWN HERE IS COMET C/2012 S1 AS IT WAS VAPORIZED IN 2013—A COLLECTIVE ENDEAVOR BY AMATEUR DISCOVERERS ALL OVER THE WORLD.

When Dr. Karl Battams started his career at the U.S. Naval Research Laboratory (NRL) 15 years ago, he was an astrophysics graduate, eager to do almost anything in his field. Inheriting a languishing citizen science project certainly qualified as "anything." After more than 15 years, that project has now produced some of the most scientifically exciting discoveries of Battams' career.

Named for a type of comet that passes extremely close to the sun, the Sungrazer project enables the identification of previously unknown comets with the help of anyone willing to look through a library of images from two NRL space-based imaging telescopes: the Large Angle and Spectrometric Coronagraph (LASCO) telescopes on the joint European Space Agency/NASA and Heliospheric Observatory (SOHO), and the Sun-Earth Connection Coronal and Heliospheric Investigation (SECCHI) instrument suite on the Solar Terrestrial Relations Observatory (STEREO).

The multidecades-volume of data from these satellites are publicly available online for anyone who would like to join the comet hunt.

"All someone really needs to find comets is an internet connection and lots of patience," Battams said.

Originally started at NASA in 2001, the Sungrazer project fell dormant in early 2003 after its original researcher and student assistant left. Late that same year, however, NRL's Solar and Heliospheric Physics Branch took on the administration role, and the program resumed with renewed interest by amateur astronomers and continued funding by NASA. Since then, participants for Sungrazer have made more than 3,600 discoveries of previously unknown near-sun comets.

The youngest Sungrazer participants to find comets have been around 13 years old, according to Battams. (Some of those same teenagers who found comets for the project are now adults finishing their PhDs.) Although the list of names of active participants is constantly changing, the core number stays relatively stable. Generally, Battams said, it's a group of about 100 primaries from around the world who have generated most of the findings.

Well over half of all cataloged comets in recorded history were discovered through this project, but despite more than 23 years of SOHO data Battams doesn't recommend looking through old images to find overlooked objects. He estimates 95 to 98 percent of every object to have passed through the telescope fields of view have already been "discovered" by someone. Almost all discoveries are made in the latest real-time data downlinked continuously from their parent missions.

Image by by NASA/ESA/NRL

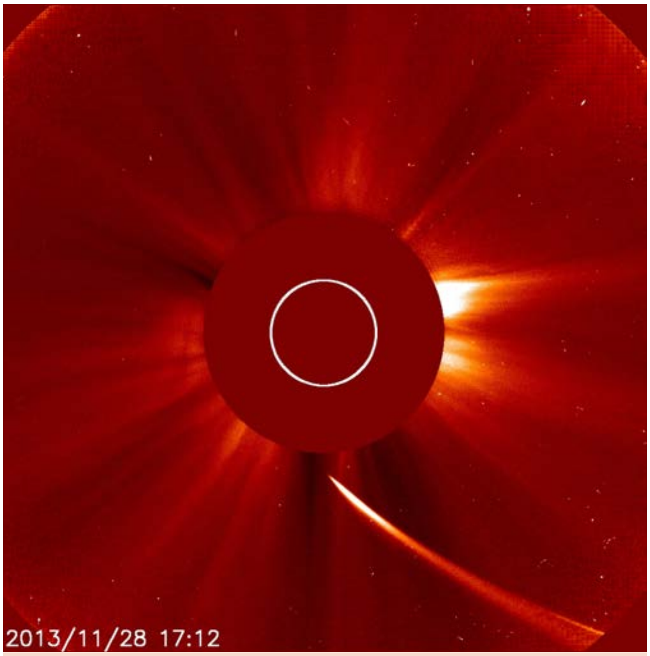
With all the attention this past year focused on NASA's Parker Solar Probe, Battams is eager to emphasize the contributions that the Sungrazer program has also made to our understanding of the sun. The project has produced several unique discoveries that shed light on heliospheric interactions with comets.

"Comets entering the very near-sun environment are like natural solar probes," Battams said. "By cataloging them and studying their interaction with the solar wind and sun's magnetic field, we can learn things about the sun that just wouldn't be possible without launching lots of very expensive missions. Comets are imperfect probes, of course, but also free and plentiful."

In 2007, the comet C/2007 P1 (McNaught) put on a stunning show when it passed through the first light imagery of NRL's SECCHI cameras, resulting in what Battams considers "one of the most spectacular image sequences of any comet in history."

"Our Solar and Heliospheric Physics group at NRL are the principal investigators of the SECCHI imaging system on STEREO, and it was the day that we opened the telescope doors for first light," Battams said. "We received our very first images and immediately visible were big bright streaks that we were not expecting. We were wondering,

In 2007, the comet C/2007 P1 (McNaught) passed through the first light imagery of NRL's Sun-Earth Connection Coronal and Heliospheric Investigation (SECCHI) cameras on the NASA Solar Terrestrial Relations Observatory spacecraft, producing bright streaks and spectacular image sequences that initially confounded Battams and his fellow researchers. Photo by NASA/NRL



This image from NRL's Large Angle Spectrometric Coronagraph (LASCO) telescope onboard the Solar and Heliospheric Observatory (SOHO) spacecraft shows comet ISON as it approaches the sun. The sun is blocked by LASCO's central occulting disk with a white circle indicating the Sun's positon and scale. ISON reached perihelion, its closest approach to the Sun, on 28 November 2013, at 18:45 UT. The comet passed just over 1 million kilometers above the solar surface. Image by NASA/ESA/NRL

'What is that? Did something go wrong? Is this stray light?' Thankfully, we quickly figured out that the spacecraft [STEREO] was rotated, and our mysterious streak was in fact comet McNaught. It was really fortuitous that we captured it in the very first images."

Another major comet event, this time in 2011, was the flight of C/2011 W3 (Lovejoy) through the sun's million-degree outer atmosphere. Battams and several other scientists from around the world coordinated more than 10 instruments on various satellites including Hubble, STEREO, and SOHO, to watch it plunge through the solar corona.

At perihelion, as the comet was closest to the sun, observations revealed large volumes of cometary material being stripped from the comet nucleus and vaporizing—with the comet's atomized material subsequently clinging to the sun's magnetic field lines, illuminating them for a few minutes. Despite seemingly surviving this journey, Lovejoy ultimately succumbed to its losses after passing the sun and heading out into space, where it completely broke apart and faded away.

"While we are interested in the comet itself, some of the most unique science here is what it tells us about the environment it's in," Battams said. "For example, studying the tail can give you information much like that of a wind sock—so solar wind speed, strength, direction; [the tail] adds unique data points."

In 2012, comet C/2012 S1 (ISON) was discovered as part of a routine sky survey by the International Scientific Optical Network (ISON), when it was about a billion kilometers from the Earth. Traveling from the Oort Cloud far outside of our solar system, ISON followed a sungrazing orbit that would take it extremely close to the sun on Thanksgiving Day 2013.

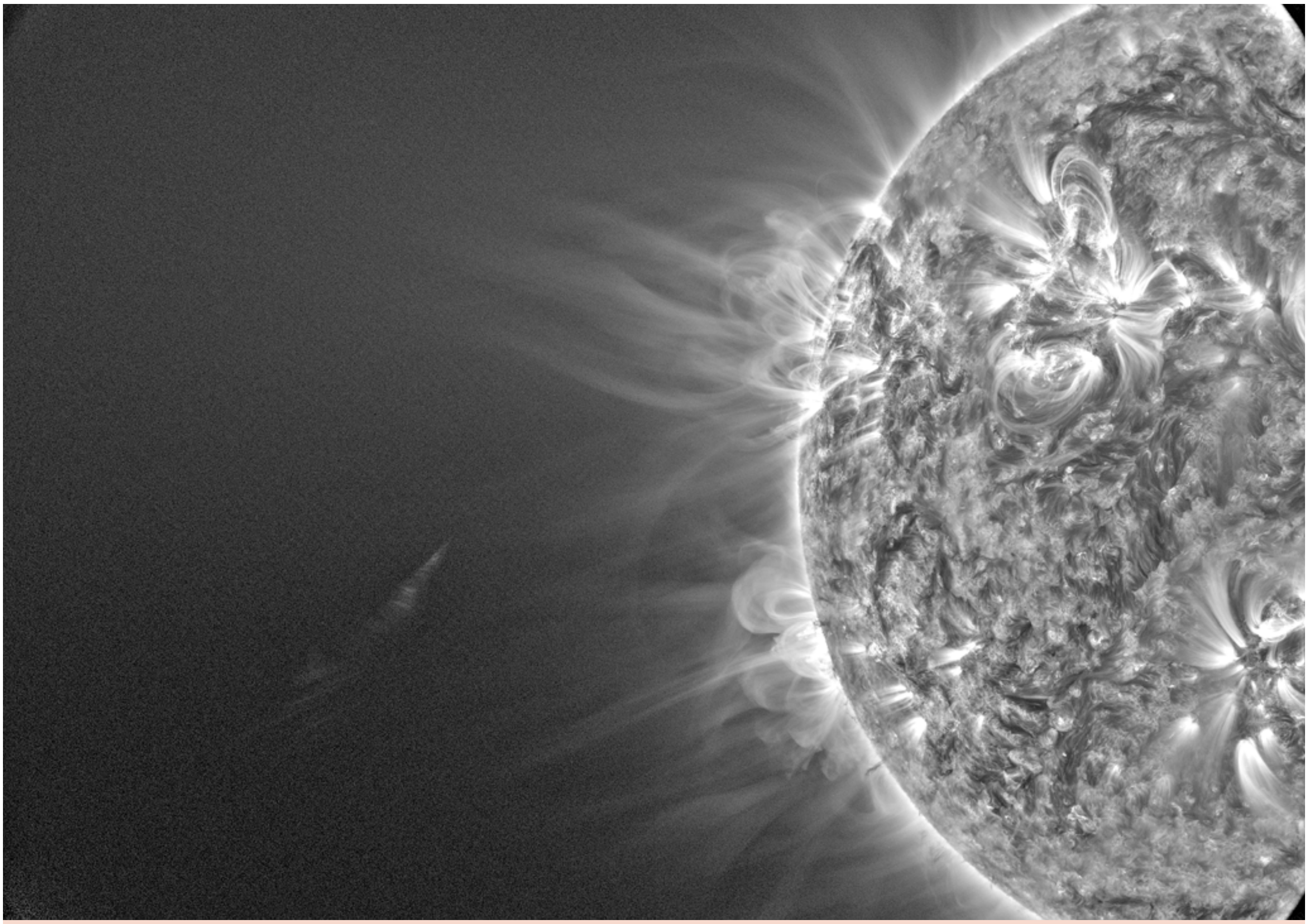
With widespread speculation that its brightness could rival that of the full moon, the comet created a lot of interest among the press, with some even saying it could become the "comet of the century."

"We knew it was going to go very close to the sun and had the potential to get very bright," Battams said. "But we always thought that 'comet of the century' was almost certainly going a little too far."

Today, after 15 years with the Sungrazer project, Battams has developed an enduring fascination with one particular family of comets that seem to have no discernible historical source.

Sometimes, larger comets that are only near-sun or sun-skirting orbiters are pulled apart by the sun's gravity into a cloud of smaller comets and become a "family," with the new smaller comets often remaining on a similar orbital path as the original comet, their "parent." The Sungrazer project has identified three previously unknown comet families, all but one of which have been traced back to parent objects somewhere in the nearly 8,000 years of recorded sightings.

The family of comets that continues to intrigue Battams is known as the Meyer group, named for amateur comet hunter Maik Meyer who first identified the family connection. The Meyer group has no identifiable parent, and new comets keep showing up—more than 200 to date. Meyer group comets are all tiny, and all look the same, but because of their high-inclination, near-sun orbit, no satellite or ground-based observer has been able to follow them long enough to determine whether they are on a closed orbit, or what their return date might be.



In this extreme ultraviolet image from NASA's Solar Dynamics Observatory satellite on 15 December 2011, sungrazing comet Lovejoy (left of center) is seen plunging through the million-degree solar atmosphere ("corona"). At perihelion, as the comet was closest to the sun, large pieces of rock were stripped from the comet and entirely vaporized by the intense sunlight. The comet's atomized material is subsequently seen clinging to the sun's otherwise-invisible magnetic field lines, briefly illuminating them and presenting researchers with an incredibly unique view of the local magnetic structure of the corona. Image by NASA

What Battams does know is that they are not following a short period path, but one that is more likely on the order of at least decades; it could be centuries. Beyond that, he only has a lot of questions.

"We know literally nothing about them; we don't where they came from, where they are going to, their orbital trajectory, or their size. We're not even certain they're actually comets [versus asteroids]," Battams said. "They are an absolute mystery and I would dearly love to know what their deal is. Of all the Sungrazer project discoveries, these are the ones that intrigue me the most."

In 2018, Battams was honored to learn that main-belt asteroid 2001 FF18 had been renamed in his honor in recognition of his 15-year stewardship of the Sungrazer project. Accompanying the announcement of the asteroid's renaming to Asteroid 29598 (Battams) was the following citation:

"Karl Battams . . . is an astrophysicist and computational scientist at the U.S. Naval Research Laboratory in Washington, D.C. He has been in charge of the Sungrazer Project since 2003, overseeing most of the project's [more than 3,400] sungrazing comet discoveries, and has contributed to the study of numerous near-sun comets."

While delighted to receive the recognition, Battams continues to ponder whether NASA will ever attempt to probe his asteroid.

About the author:

Sara Francis is a writer with the U.S. Naval Research Laboratory.

CLEMENTINE

THE SMALL LUNAR EXPLORER THAT PRODUCED BIG RESULTS

By Daniel Parry

TWENTY-FIVE YEARS AGO, ON 25 JANUARY 1994, THE DEEP SPACE PROGRAM SCIENCE EXPERIMENT—BETTER KNOWN AS "CLEMENTINE"—WAS LAUNCHED FROM VANDENBERG AIR FORCE BASE, CALIFORNIA.

Developed and built by the U.S. Naval Research Laboratory (NRL), Clementine's primary mission was in-space testing of advanced technologies for high-tech, lightweight missile defense. The relatively inexpensive, rapidly built spacecraft constituted a major revolution in spacecraft management and design and also contributed significantly to lunar studies.

In addition to the scientific value, the mission presented clear benefits to the Department of Defense (DoD), with the intent of flying the craft past the near-Earth asteroid Geographos to provide a meaningful target against which to flight-qualify advanced lightweight missile defense technologies. Clementine's high closing velocity on the asteroid, a cold body flying against a deep space background, presented a two-fold opportunity to test DoD missile-intercept applications and NASA space exploration requirements.

Fostering a New Era

In the early 1990s, NASA approached the Strategic Defense Initiative Organization (renamed the Ballistic Missile Defense Organization in 1994) proposing a joint NASA/DoD space mission that could prove beneficial to the future objectives and capabilities of both agencies. The purpose of the mission was to test new state-of-the-art technology and its ability to function and withstand prolonged exposure to deep space, and to determine the collaborative functionality of a major multiagency project.

Using Earth's moon as a focal point, the mission would test lightweight sensory equipment, attitude control systems, and software. To accomplish mission goals Clementine required a multimode propulsion system, computers, inertial measurement units, and an array of cameras that included an ultraviolet/visible camera (UVVIS), near-infrared camera (NIR), high-resolution camera (HIRES), laser rangefinder (LIDAR), long-wavelength infrared camera (LWIR), and two star-tracker cameras designed and built by the Lawrence Livermore National Laboratory in Livermore, California.

Faster, Better, Cheaper

In early 1992, DoD and NASA selected NRL's Naval Center for Space Technology (NCST) to build this spacecraft. Because of the sponsor's funding limits and the timeline to rendezvous with Geographos, the Clementine mission became known in retrospect as an exemplar of the "faster, better, cheaper" management approach.

At a 1998 IEEE aerospace conference, Dr. Donald Horan, then chief scientist and director of the Clementine program, said "Some reasons why Clementine could be considered faster, better, and cheaper are inherent to the Naval Center for Space Technology. Clementine was the 81st satellite built by NCST since 1960 and, over the years, competition for space dollars had forced NCST to become efficient."

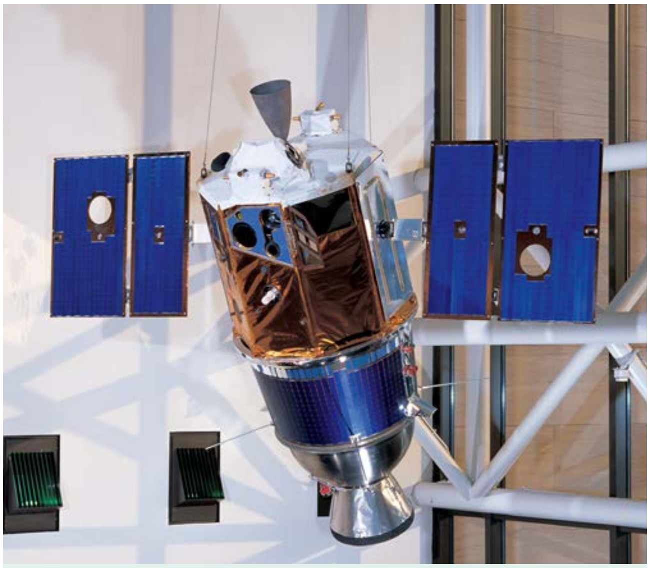
NRL engineers eagerly accepted the challenge, developing the mission design, spacecraft engineering, spacecraft manufacturing, flight-logistics and flight operations in less than a two-year period.

To the Moon!

Formally considered the Deep Space Program Science Experiment, the project was soon dubbed Clementine, from the American folk ballad "Oh My Darling," because the lightweight spacecraft would not only be "mining" the geology of the lunar surface, but carried only enough fuel to complete its mission before being "lost and gone forever."

Demonstrating that smaller, highly capable satellites were obtainable at a cost below $100 million, Clementine was completed in 22 months at a cost of less than $80 million. It was launched aboard a Titan IIG rocket from Vandenberg Air Force Base. After two Earth flybys, Clementine entered lunar orbit on 19 February 1994 and was positioned into an optimal five-hour polar orbit to fully map the lunar surface.

In an FY1994 report to Congress, President Bill Clinton stated that among the nation's notable achievements in aeronautics and space was the launch of the Deep Space Probe, Clementine. "The highly successful launch of the Clementine Deep Space Probe tested 23 advanced



Clementine engineering model as viewed at Smithsonian's National Air and Space Museum. Photo by Eric Long/National Air and Space Museum

Photo by NRL

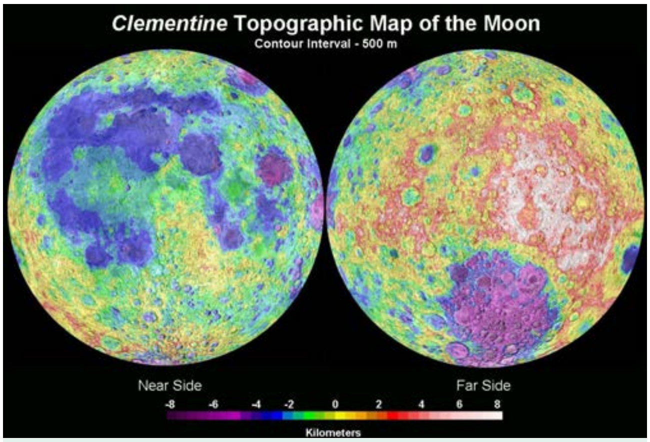
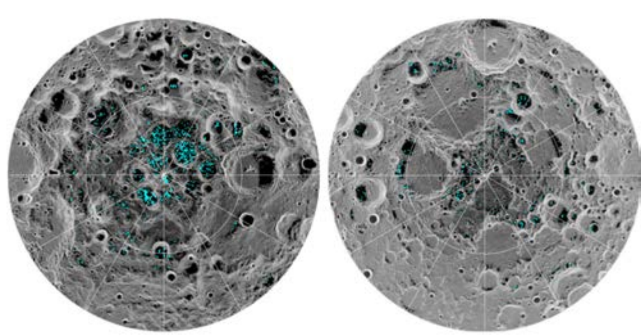


Image of Clementine laser altimetry (red is high, purple is low) showing the nearside and far-side of the moon. Image by NASA

technologies for high-tech, lightweight missile defense," he said. "The relatively inexpensive, rapidly built spacecraft constituted a major revolution in spacecraft management and design; it also contributed significantly to lunar studies by photographing 1.8 million images of the surface of the moon."

Between 26 February and 22 April, Clementine was able to deliver the nearly two million digital images of the moon to the NASA Deep Space ground network and NRL's satellite ground-tracking station located in Pomonkey, Maryland.

Images were quickly made available to scientists and the public using the then-nascent World Wide Web. However, in 1994, serving this amount of data challenged all but top supercomputer sites. To accomplish this task, NRL's Center for Computational Science hosted the images and developed sophisticated data handling and caching strategies for distributing and retrieving the large data set across multiple storage subsystems. The resultant system enabled researchers, as well as K-12 students from around the world, to quickly browse the entire imagery collection and download selected subsets from even slow Internet connections, such as those served by dial-up modems.



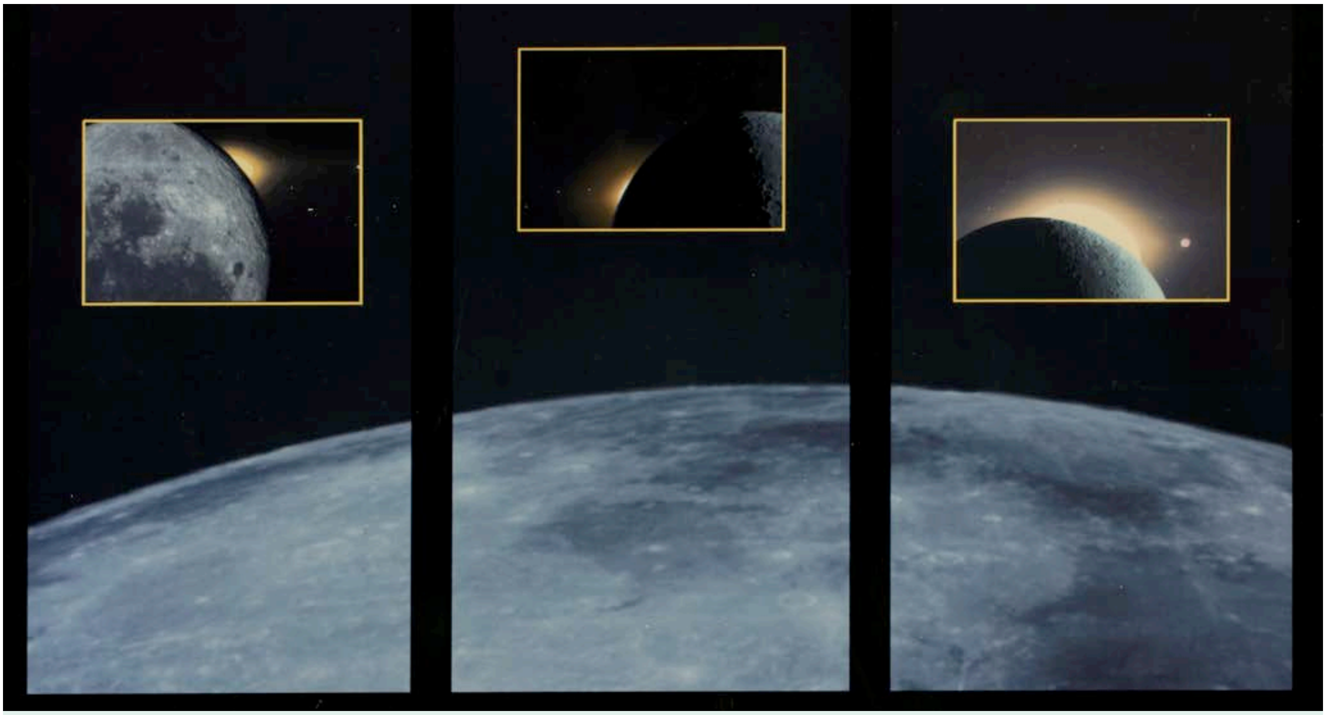
This shows the distribution of surface ice at the moon's south pole (left) and north pole (right), detected by NASA's Moon Mineralogy Mapper instrument. Blue represents the ice locations, plotted over an image of the lunar surface, where the gray scale corresponds to surface temperature (darker representing colder areas and lighter shades indicating warmer zones). The ice is concentrated at the darkest and coldest locations, in the shadows of craters. This is the first time scientists have directly observed definitive evidence of water ice on the moon's surface. Image by NASA

After completing its two-month mapping mission orbiting the moon, the craft was designed to then use phasing loops around Earth and fly past the near-Earth asteroid Geographos. Unfortunately, after leaving lunar orbit May 3, an onboard computer glitch inadvertently caused a thruster to fire, expending the remaining fuel and leaving the spacecraft spinning in a geocentric Earth orbit.

This is a final look at the Clementine DSPSE spacecraft, which is mated to its launch vehicle, the Titan IIG (two i's, not two ones). Here, the nose fairing is being lowered to enclose Clementine in its new home during launch.

A Legacy Not Lost

Although its attempt at flying past the asteroid failed, Clementine provided answers to many questions about the moon that remained from the Ranger and Surveyor unmanned programs and the Apollo-era manned missions. Observations included imaging at various wavelengths including ultraviolet and infrared, laser ranging altimetry, and charged particle measurements. These observations were for the purposes of assessing



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surface mineralogy, obtaining lunar altimetry, and determining the size, shape, rotational characteristics, surface properties, and cratering statistics of the moon.

When scientists further reviewed the data from Clementine, they made a major scientific discovery: the possible existence of ice within some of the moon's craters. In early 1998, NASA's Lunar Prospector confirmed this discovery when NASA scientists announced that the spacecraft's neutron spectrometer instrument had detected hydrogen at both lunar poles, theorized to be in the form of water ice.

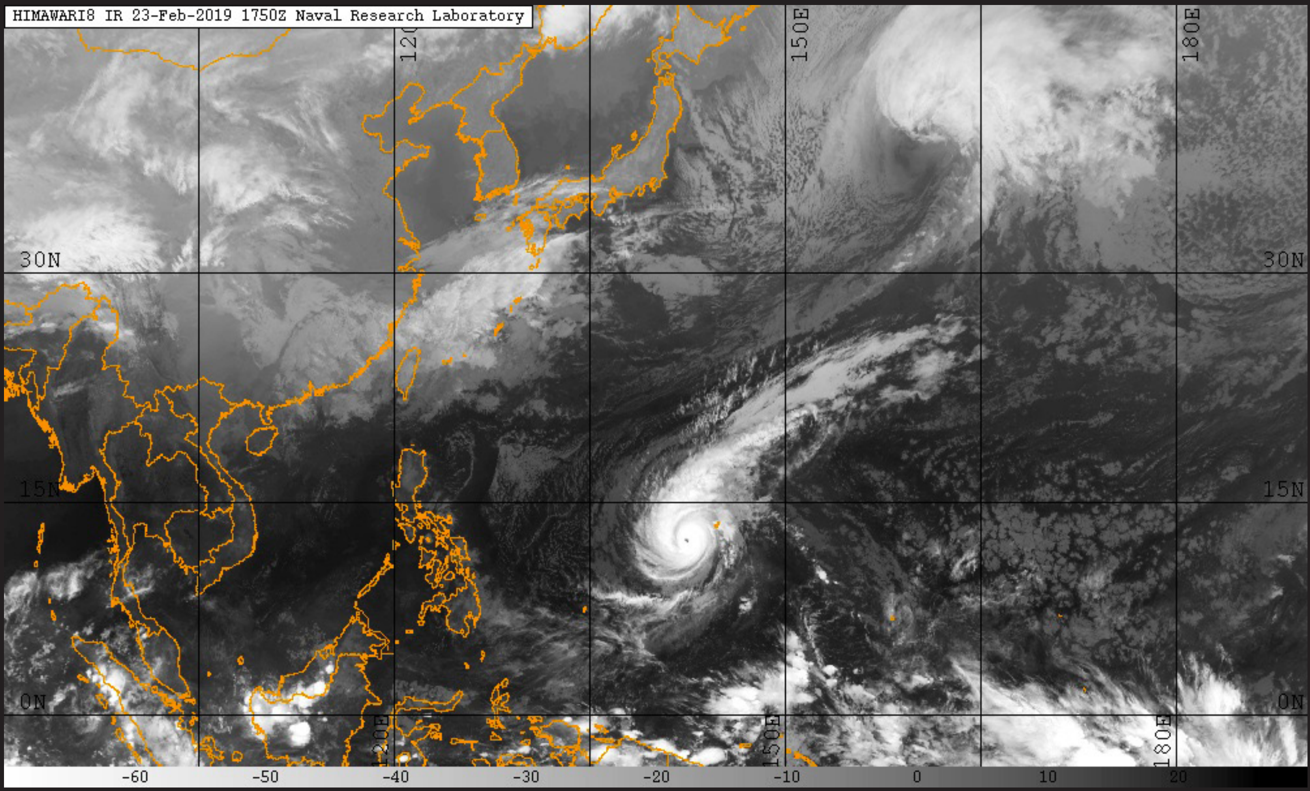
Encouraged by the valuable data gathered by the Clementine mission and a new vision for space exploration, including a planned return to the moon for the purpose of eventual human missions to Mars, NASA launched the Lunar Crater Observation and Sensing Satellite and companion Lunar Reconnaissance Orbiter. The 2009 mission was launched to better understand the moon's topography and composition and search for water ice in the dark shadows of one of the moon's many craters.

NASA concluded that conditions in large areas of the lunar south pole proved favorable enough to accumulate water ice deposits and accommodate a series of other compounds such as sulfur dioxide, carbon dioxide, formaldehyde, ammonia, methanol, mercury, and sodium, further confirming critical discoveries of the Clementine mission.

Twenty-five years later, Clementine continues to inspire the quest for answers to our closest celestial body and serves as a benchmark for innovative lunar exploration and beyond. The mission offered many benefits to the U.S. space program—including its primary military mission to qualify lightweight technology—and returned valuable lunar data for the international civilian scientific community that exceeded mission science objectives. Its scientific observations have built the most comprehensive lunar multispectral geological map to date, demonstrating near-autonomous spacecraft operations and providing a pathway for reduced flight operations costs on many future DoD/NASA space collaborations.

About the author:

Daniel Parry is a writer with the U.S. Naval Research Laboratory.



Generated at the Naval Research Laboratory Marine Meteorology Division, a Himawari-8Advanced Himawari Imager infrared image shows Super Typhoon Wutip passing south of Guam in the western Pacific Ocean on 23 February 2019. The Marine Meteorology Division, located in Monterey, California, conducts cutting-edge research in the atmospheric sciences and develops high-resolution meteorological analysis and prediction systems and other decision products to support Navy, Department of Defense, and other customers. Photo by US Navy

FUTURE FORCE is a professional magazine of the naval science and technology community published quarterly by the Office of Naval Research.

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