National Aeronautics and Space Administration

Cutting edge

Goddard's Emerging Technologies

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Eyes on Earth

Looking Forward to New Views of Our World

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Strategic Goddard Investments In Earth Observations Lay Groundwork for New Opportunities

Long-term, strategic investments in Goddard's Earth science remote sensing technology have positioned NASA to tackle a new era of Earth observations.

The 2017 Earth Science Decadal Survey (DS) as set forth by the National Academies of Science, Engineering and Medicine, focuses on addressing the most pressing scientific questions facing the global community with an eye towards potential needs in the following decade. The four major priorities for Designated Observable this decade include the following missions: the Aerosols and Clouds, Convection and Precipitation (ACCP); the Surface Biology and Geology (SBG); Surface Deformation and Change (SDC); and Mass Change (MC). Currently these Designated Observables, including the GSFC-led ACCP, are in the study phase hoping to move into Pre-Phase A mission planning this spring. The 2017 Decadal also detailed targeted observables to be addressed in the following decade that require continued investment in the development of technologies and mission concepts to meet future needs. The targeted observables include: greenhouse gases; ice elevation; ocean surface winds and currents; ozone and trace gases; snow depth and snow water equivalent; terrestrial ecosystem structure; and atmospheric winds.

Goddard scientists and engineers, with support from the Internal Research and Development (IRAD) and other investments, helped position NASA to tackle some of the most important Earth science questions with crucial measurements to keep up with a changing world (See breakout boxes, Page 3). This issue looks at Goddard's Earth science innovators, and the people and projects opening new windows of observation onto humanity's home planet. ❖

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Spring 2021

About the Cover

Simulations like this help scientists make connections between phenomenon like dust from the Sahara affecting the behavior and growth of tropical storms in the Atlantic and fertilizing South American rain forests. A new generation of Earth-observing and post-processing technologies will enable new and sustained data collection on global systems including the transport of dust, particulates, aerosols, and clouds as well as convection. Artificial intelligence and machine learning will assist in culling through these vasts amount of data to distill the valuable information. These data, in turn, will improve weather forecasting and humanity's understanding of Earth's changing climate.

(Photo Credit: NASA/Goddard/Scientific Visualization Studio)

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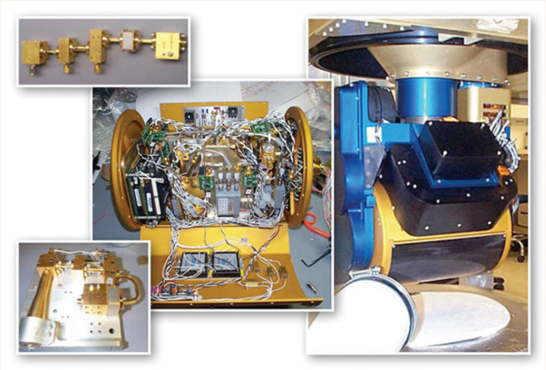
Earth Science Opportunities At-A-Glance

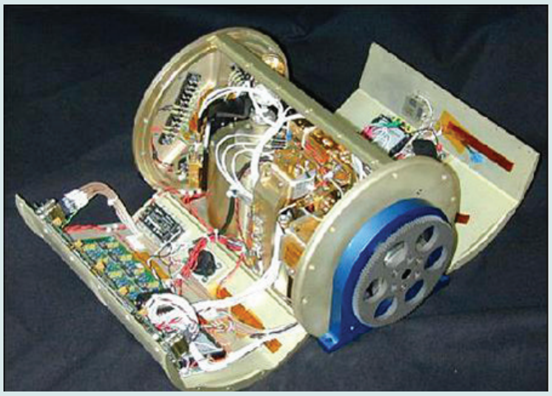
CoSSIR
Compact Scanning Submillimeter-wave Imaging Radiometer

This airborne, 12-channel, (183 - 874 GHz) total power imaging radiometer was mainly developed for the measurements of ice clouds, but it can give an estimation of water vapor profiles and snowfall rates as well. First flown in 2002, and now part of the IMPACTS field campaign, CoSSIR is under the direction of Ian Adams.



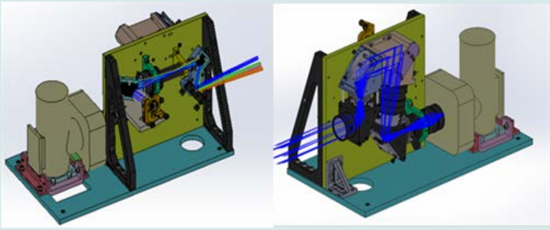
HyMAS
Hyperspectral Microwave Atmospheric Sounder

"Hyperspectral microwave" is used for all-weather sounding, capable of detecting 52 channels in two microwave bands and effective for profiling temperature and the ingredients that produce storms. Paul Racette worked with MIT's Lincoln Laboratory to help better understand the distribution and temperature of water in the atmosphere.



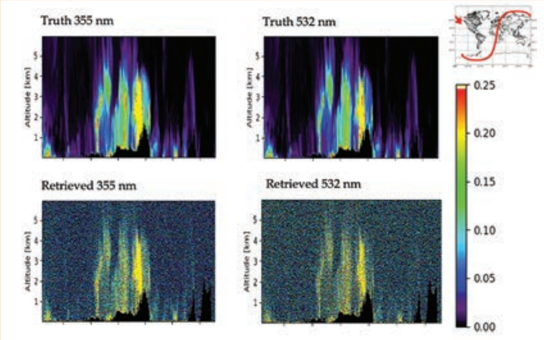
CASALS
Concurrent Artificially Intelligent Spectrometry and Adaptive Lidar System

CASALS will achieve lidar mapping of the Earth's surface from orbit, using innovative passive laser beam scanning, combined with hyperspectral imaging. This fall, led by PI Guangning Yang, a benchtop system will range horizontally a few km to calibration and vegetation targets. The goal next year is autonomous demonstration of the system on a high-altitude, long-duration, sub-orbital platform.



MADCAP-CAPER
Maturing and Demonstrating Cloud-Aerosol Lidar and Polarimeter Capabilities for Earth Science Decadal Survey Response

This continuing software effort seeks to enable multi-angle polarimeters working with lidar to distinguish aerosols in more difficult to interpret locations, including over clouds and complex land formations. PI Peter Colarco and his team already demonstrated positive results with data simulating clear skies or thin cirrus clouds.



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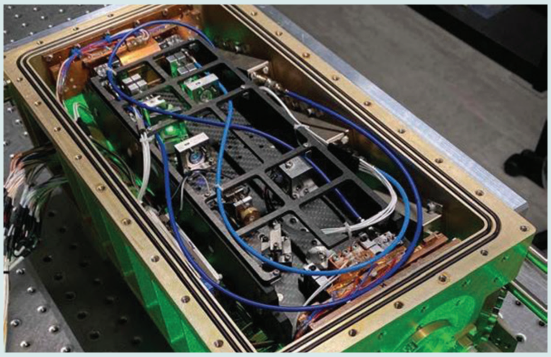
Earth Science Opportunities At-A-Glance

SWESARR
Snow Water Equivalent Synthetic Aperture Radar and Radiometer

A first-of-its-kind microwave instrument, SWESARR proved successful at remotely sensing snowpack conditions that would reveal snow water equivalent, or SWE: critical for understanding the world's water resources and the impact that climate change may have on them. Paul Racette worked with scientist Batu Osmanoglu on this sensor, which flew on NASA's SnowEx campaign in 2019/2020.

TOMCAT
Time-varying Optical Measurements of Clouds and Aerosol Transport

This miniaturized lidar gives scientists the "where" to polarimetry's "what." TOMCAT would transmit laser light toward Earth and then use the returning signal to determine the vertical location of clouds and the miniscule particles lofted into the atmosphere during fires, dust storms, volcanic eruptions, and other events. PIs are John Yorks and Matthew McGill.



Polarimetry Made Simple

The next generation of polarimeters could benefit from a new metasurface technology developed by researchers at Harvard working with Goddard scientists.

Sunlight traveling through the atmosphere becomes polarized when it reflects off water vapor, ice, biogenic aerosols, dust, and other particulates. Goddard Earth scientist Kerry Meyer is working with Harvard partners who developed a metasurface technology that, using one flat optical component, can analyze light along four chosen polarization directions, allowing for a full characterization of light's polarization state.

"Up until recently," Meyer said, "polarimeters have been pretty large instruments, and depending on the measurement strategy, could involve lots of moving parts and different optics. This metasurface technology splits the incoming signal into all four states. It's pretty awesome."

Without all the moving parts, the Harvard technology could enable polarimetry in SmallSats and CubeSats, but could also be scaled up to power larger missions at a significant savings over existing technology, he said.

While the technology is still in early development, Goddard scientist Dan Miller said a polarimeter is expected to fly on the Aerosol, Cloud, Convection and Precipitation (ACCP) mission recommended in the 2017 Earth Decadal Survey.

Expected to go into Pre-Phase A development this spring, ACCP would, among other things, combine polarimetry with lidar data to provide new insights into the clouds and particulates in the atmosphere and how they affect life on Earth.

"The combination of a lidar and a polarimeter in orbit, looking at the same target, tells you both what you're looking at and the vertical distribution in the atmosphere — where it is," Miller said.

Continued on page 5

The partnership with Goddard gave Harvard postdoctoral researcher Noah Rubin valued insight into the science use cases for his technology.

"Working with our new peers at Goddard has been great," Rubin said. "My team at Harvard were primarily concerned with new physics and optical technologies enabled by controlling light at the nanoscale. It's rare, however, that we get the chance to interact with potential end-users in such a direct way, not to mention at such an early stage in a new technology's development."

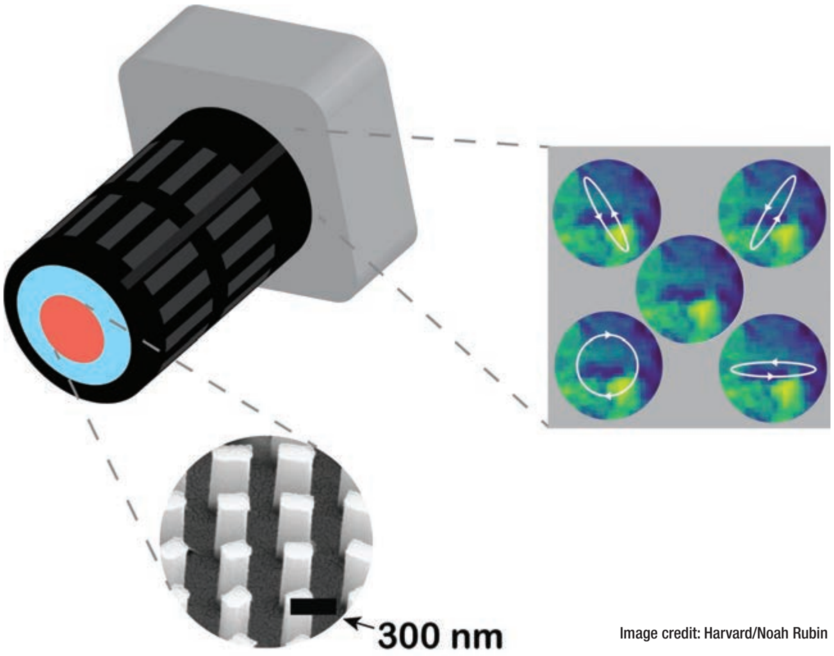


Image credit: Harvard/Noah Rubin

Kerry Meyer is working with a new metasurface material developed by Harvard researchers to develop new lightweight polarimeters.

"The team at Goddard has helped us to understand their scientific requirements," he added, "which informed how we think about the new metasurface technology. We've had a very interesting scientific exchange overall."

Having worked on the polarimetry-based missions, Glory, and Advanced Composition Explorer (ACE), Miller said he is excited to have a polarimeter in orbit. He is looking forward to the Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission, that will be the next major mission to fly a polarimeter in Earth orbit (See related story, Page 6).

"For me," Miller said, "the 'a-ha' moment on the cloud side was realizing that the effective radius of water droplets in the clouds determines how light gets scattered, and that will tell you the mass of the water in the cloud.

"When we talk about important cloud processes in the atmosphere, it all revolves around this distribution," he added. "Different size and distributions of water droplets exist at different heights in cloud formations at different stages of the cloud's growth and evolution."

For Earth scientist Ed Nowottnick, the Harvard technology makes distributed observations of clouds and aerosolized particles one step closer to reality.

"I could see flying this sensor in space as a constellation," he said. "If you could put up multiple copies of this thing, you can improve your coverage over time. Then, you're really going a long way towards understanding these processes."

Payouts would include better forecasting of weather, aerosols, and clouds, and a stronger understanding of how climate change could affect these processes in the future.

Better data on the circular polarization of sunlight, in particular, could yield a wealth of data on weather and climate, Meyer said. This happens after sunlight has been scattered through clouds, ice or aerosols more than once, and has not traditionally been tracked, because it is a very small signal. "You have to have an instrument that can measure that signal and separate it from the noise."

Goddard scientists like Meyer look forward to an era of Earth-observing CubeSats operating cooperatively in swarms. These distributed observations could complement the ACCP mission, tracking similar phenomena and adding to a global dataset on aerosols, clouds, convection and particulates in the atmosphere.

"These are your exploratory polarimeter technologies," Meyer said of the Harvard partnership, "the next generation beyond ACCP." ❖

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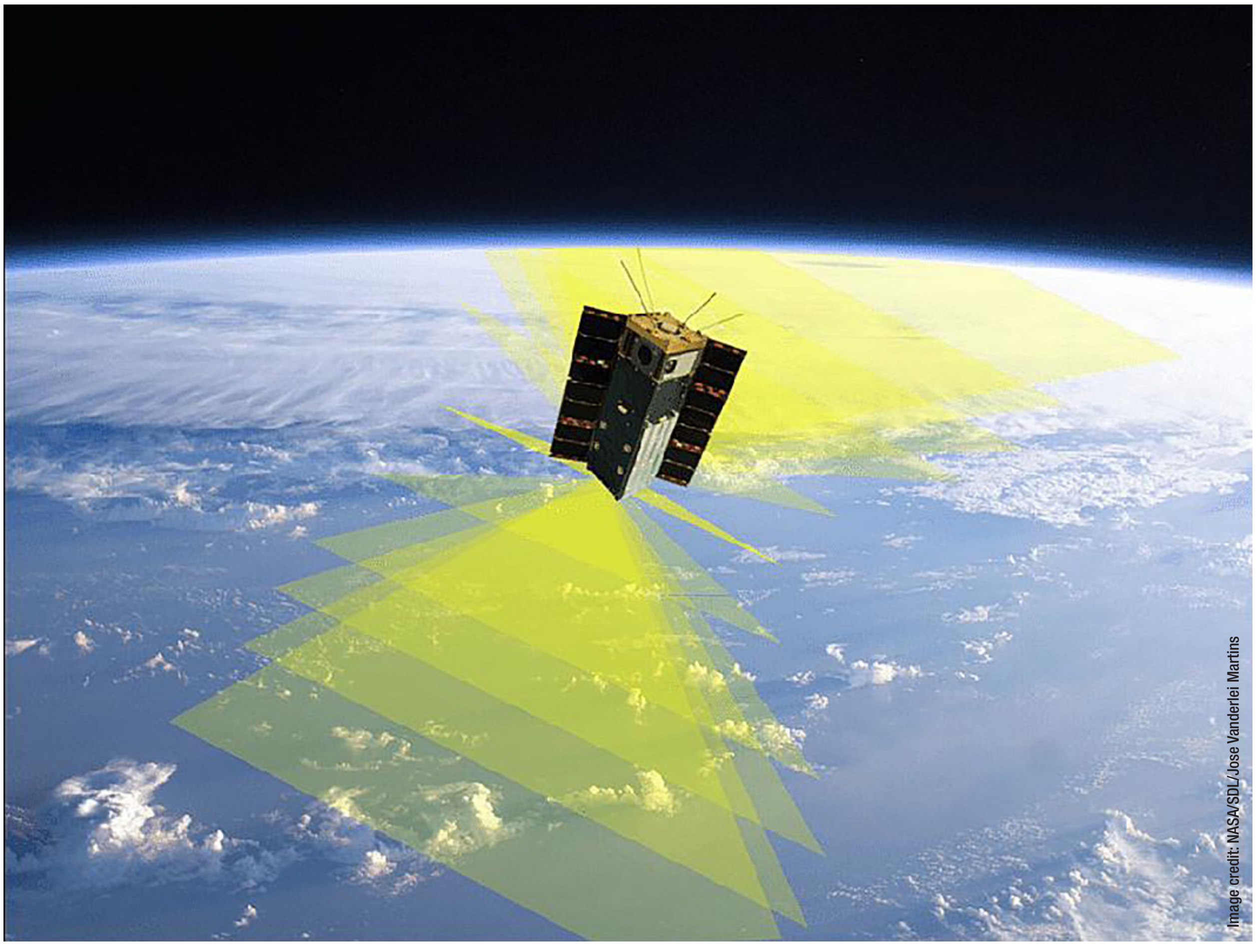
Endowing Satellite Swarms With a Hive Mind



A swarm of SmallSats like this one and others with more narrow-angle, high-resolution polarimeters could potentially revolutionize understanding of weather formation and processes.

Swarms of SmallSats buzzing around Earth could coordinate amongst themselves to collect data on important weather patterns at different times of the day or year, and from multiple angles. Such swarms could revolutionize scientists' understanding of weather and climate changes.

Goddard engineer Sabrina Thompson is working on software to enable SmallSats to communicate with each other, identify high-value observation targets, and coordinate attitude and maneuvering to get different views of the same target.

"We already know that Saharan dust blowing over to the Amazon rainforests affects cloud formation over the Atlantic Ocean during certain times of the year," Thompson said. "How do you capture that cloud formation? How do you tell a swarm of satellites what region and time of day is the best to capture that phenomenon?"

Under Thompson's plan, scientists would establish a set of requirements for observations and define high-value targets. Then the software would take over, enabling a spacecraft swarm to figure out how to move relative to one another to best observe these targets. Strategies might also change based on time of day, season, or the region being observed, she said. The spacecraft would use onboard machine learning to improve viewing strategies over time as well.

Individual spacecraft could even use something called differential drag control — manipulating the forces caused by Earth's atmosphere dragging against the orbiting craft — to control the relative position of spacecraft in the swarm, she said.

"With multiple spacecraft in one formation to view the same target," Thompson said, "you can see a cloud, for instance, not just from the top, but from the sides as well." In a different formation, you can see that cloud at

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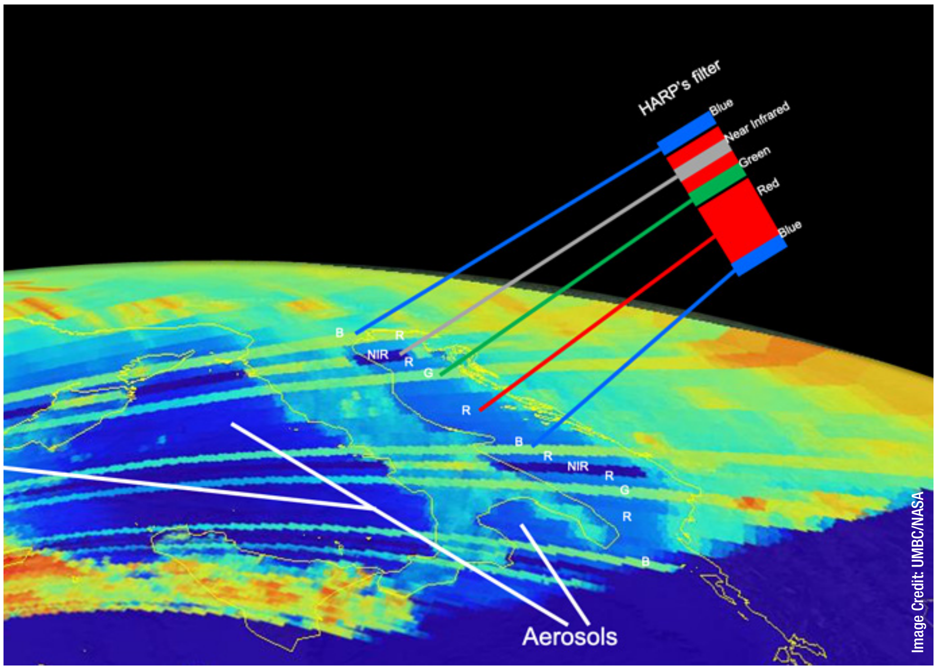
different stages of its life-cycle from multiple SmallSats passing at different times.



The HARP CubeSat sent back a first light capture on April 16, 2020, showing clouds and aerosols over the coastlines of Italy, Sardinia and southeastern Europe.

Working with University of Maryland, Baltimore County, professor Jose Vanderlei Martins, Thompson helped develop the Hyper-Angular Rainbow Polarimeter (HARP) CubeSat that launched from the International Space Station (ISS) just over a year ago. An updated version called HARP2 will fly on the Plankton, Aerosol, Cloud, ocean Ecosystem (PACE) mission planned for launch in 2023.

A swarm of SmallSats sharing information and coordinating coverage could advance weather forecasting, disaster reporting, and climate modeling in the long term, Vanderlei Martins said. To get there, scientists need the combination of wide and narrow fields of view and high-resolution imagery to better understand the dynamics of weather system development.

"Ideally, I like to have a satellite with a wide field of view observing larger phenomenon," he said. "However, a small satellite covering a large area cannot have a high resolution, so you can use it as a surveyor type of satellite to identify the area of interest. Then you have others with a narrower field of view, getting higher resolution, getting much more detail."

Enabling the swarm to make decisions and share information is crucial, Vanderlei Martins said. "These sorts of decisions need to be made in minutes. You don't have time for ground control to be involved."

Reducing reliance on ground control and communications networks also frees up resources for SmallSat missions with limited budgets, Thompson said.

An aerospace engineer working towards an Atmospheric Physics degree at the University of Maryland, Baltimore County, Thompson went back to school because she said she wanted to learn more about the Earth science requirements that drive her work as an innovator. "I also really wanted to understand climate change."

Polarimeters can provide a wealth of data about particles suspended in the atmosphere. From smoke, ash, and dust to water droplets and ice, each species of particle polarizes light reflected from it in detectable ways, Thompson said. "How aerosols and clouds interact is crucial to understanding climate change," she said.

"At a basic level, my research involves evaluating the geometry between instruments on the satellite and the sun," Thompson said. "These instruments are passive. They require a certain geometry relative to the ground target and Sun in order to retrieve the science data we want."

Her algorithms will determine the most suitable combinations of orbit and instrument field of views to give the largest probability of observing a cloud with the appropriate geometry to retrieve science data. Then it would plan and execute maneuvering schemes for each spacecraft to achieve those geometries. Understanding the structure and development of clouds — cloud tomography — ties in with the Aerosols and Clouds, Convection and Precipitation (ACCP) mission identified in the 2017 Earth Decadal Survey (see related articles, Pages 2 and 3). Both Jose Vanderlei Martins and Sabrina Thompson believe their swarm technology complements ACCP's mission goals.

Thompson's study also fits well with ongoing autonomous Navigation, Guidance, and Control (autoNGC) efforts at Goddard (*CuttingEdge*, Fall 2020, Page 10). ❖

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New AI Technology Could Speed Up Fault Diagnosis Process in Spacecraft

New artificial intelligence technology could speed up physical fault diagnosis in spacecraft and spaceflight systems, improving mission efficiency by reducing down time.

Research in Artificial Intelligence for Spacecraft Resilience (RAISR) is a program developed by Pathways Intern Evana Gizzi, who works at the Goddard Space Flight Center in Greenbelt, Maryland. With RAISR, artificial intelligence could diagnose faults real-time in spacecraft and spaceflight systems in general.

"The spacecraft reporting a fault is like a car with a check engine light on," Gizzi said. "You know there is an issue, but can't necessarily explain the cause. That's where the RAISR algorithm comes in, diagnosing the cause as a loose gas cap."

Right now, the ability to make inferences about what is happening that go beyond traditional 'if-then-else' fault trees is something only humans can do, Gizzi said. Current fault tree diagnosis depends on the physics being simple and already known to engineers and scientists. For instance, if an instrument's temperature drops too low, the spacecraft can detect this situation and turn on heaters. If the current in a line spikes, the spacecraft may work to isolate the offending circuit. In both cases, the spacecraft simply knows that if 'A' happens, respond by doing 'B'. What the spacecraft cannot do is figure out what caused these events, especially in unexpected fault cases: whether the spacecraft entered Earth's shadow or a micrometeroid damaged a circuit.

These types of conclusions require the ability to follow a logical chain of non-trivial inferences — something like human reasoning, Gizzi said. The AI might even be able to connect the spacecraft's decreased temperature with a malfunction in its internal heat regulation system: an example of a more catastrophic fault.

Referring such faults to a human on the ground does not just take time, but costs valuable resources in terms of communications networks and bandwidth for smaller missions in Earth orbit, or even for exploring distant planets, where bandwidth to controllers on Earth is limited by distance.

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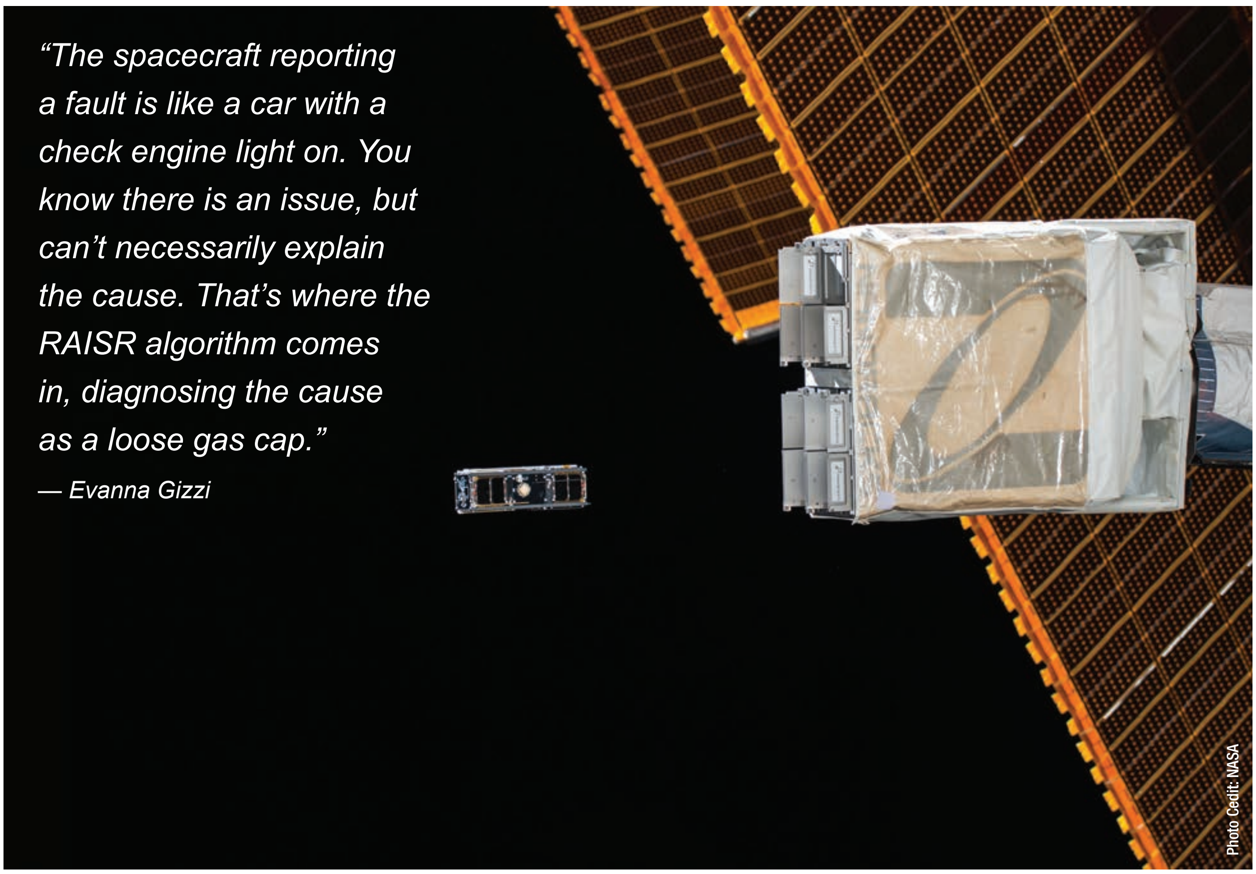

RAISR

In other circumstances, like orbiting behind another planet or the Moon, contact is simply not available. Computers also excel over human controllers when a proper inference needs to be done extremely fast using several disparate types of data.

In its current stages, RAISR does not actively control the spacecraft in any way, but facilitates diagnosis by finding associations that a human may miss.

Michael Johnson, the Engineering and Technology Directorate chief technologist at Goddard, said current safe modes waste valuable time because science data collection ceases, whereas a technology that could diagnose and address a fault might lead to a quicker return to normal flight operations.

RAISR uses a combination of machine-based learning and classical AI technique. While machine learning-based techniques can be particularly useful in diagnosing faults, its performance depends on having a large amount of diverse data, Gizzi said, and therefore usually addresses faults that have happened in the past. With anomalies, which are faults that have never been experienced, there simply may not be enough data to create sound reasoning with machine learning-based techniques. That is where AI steps in, Gizzi said, facilitating reasoning in more complicated situations that don't have previous data to inform decisions.

Gizzi's technology helps make connections that are extraordinarily difficult to be made by humans, said Conrad Schiff, an assistant chief for technology in the software engineering division at Goddard.

"It's not just an automated system," Schiff said. "It's an automated system that attempts to reveal how it arrived at the 'whodunit.' Laying out the evidence like a detective at the end of a mystery novel, so that we all can see who is guilty of murder — that's the same principle here. It understands these associations, it helps us understand its reasoning in arriving at its conclusion."

RAISR enables better collection of data and observations by reducing resources needed for the maintenance of the systems themselves, Schiff added. "It's less glamorous, it's grittier, but it's making sure the health and safety of the thing producing the data is maintained as best as we can."

In general, AI can act like an additional brain within the spacecraft, Johnson said.

"You're taking an engineer or a scientist from the lab and putting a simplified copy of them in the spacecraft, so they can make intelligent decisions in situ," Johnson said.

RAISR's next steps include a shadow demonstration on a small satellite, Gizzi said, where it can make real-time decisions to compare with ground control.

Photo courtesy of Evana Gizzi

As more missions adopt AI techniques, he said, testing approaches may have to shift. Rigorous protocols that test every possible scenario might not apply. That, combined with the cultural shift from ground-based problem resolution to letting the on-orbit systems solve problems themselves, makes putting AI in spacecraft an incremental journey, he said.

"When I think about spaceflight, it's a target for autonomous systems that just makes sense," Johnson said. "The real leap occurs when we go beyond automation to autonomy, from programming steps you know will happen to the system starting to think for itself. When you go into deep space, there are going to be things you did not program for. The need is really there." ❖

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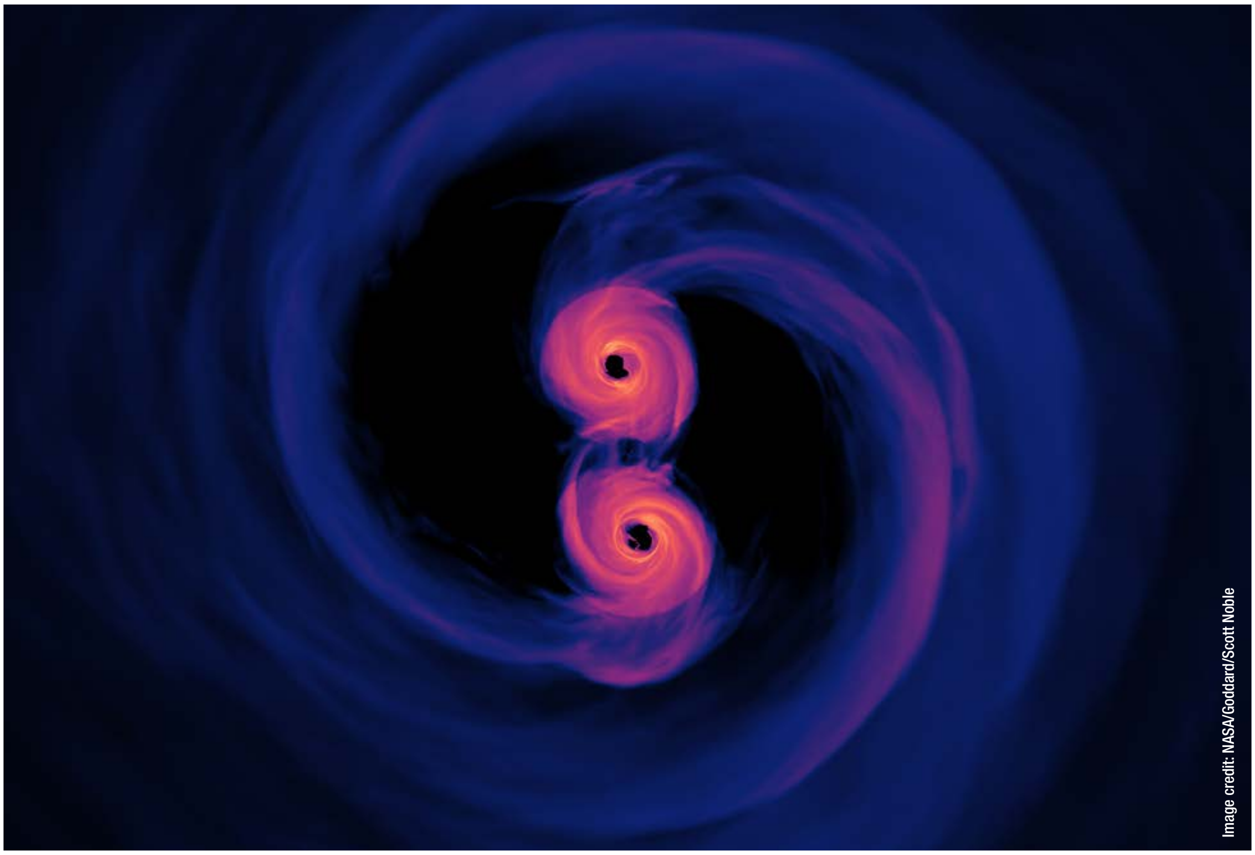
Binary Black Hole Simulations Provide Blueprint for Future Observations



Simulations like these help scientists envision the massive forces between two black holes heading for a merger.

A Goddard astronomer hopes his black hole simulations will help future missions better home in on black holes, the most elusive inhabitants of the universe.

Though black holes likely exist abundantly in the universe, they're notoriously hard to see. Scientists did not capture the first image of a black hole until 2019, and only about four dozen black hole mergers have been detected through their signature gravitational ripples since the first detection in 2016.

That is not a lot of data to work with, and scientists might look to black hole simulations to find more mergers with future missions.

Some of these simulations, created by scientists like Goddard astrophysicist Scott Noble track supermassive black hole binary systems. That is where two monster black holes like those found in the centers of galaxies orbit closely around each other until they eventually merge.

The simulations, created by computers working through sets of equations too complicated to do by hand, illustrate how matter interacts in merger environments. Scientists can use what they learn about black hole mergers to create a set of characteristics distinguishing them from stellar events, which astronomers can see, and then use the set of characteristics to confirm real-life mergers.

Noble said binary systems are multimessenger, meaning they emit both gravitational waves and influence surrounding gases, leading to unique electromagnetic emissions detectable with conventional telescopes. This allows scientists to learn about different aspects of the same system. Multimessenger observations could allow scientists to refine their models of binary systems.

"We've been relying on light to see everything out there," Noble said. "But not everything interacts with light. Two black holes don't emit light, so the only way to 'see' them is through gravitational waves.

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These are independent ways of learning about the system, and the hope is that they will meet up at the same point."

Binary black hole simulations can also help the Laser Interferometer Space Antenna (LISA) mission. This space-based gravitational wave observatory led by the European Space Agency with significant contributions from NASA, is expected to launch in 2034. Noble said if simulations determine what electromagnetic characteristics distinguish a binary black hole system from other events, scientists could detect these systems before LISA flies. These observations could be confirmed through additional detections once LISA launches.

That would allow scientists to verify that LISA is working, observe systems for a longer period before they merge, predict what is going to happen, and test those predictions.

"We've never been able to do that before," Noble said. "That's really exciting."

Noble said the simulations rely on the High-Accuracy Relativistic Magnetohydrodynamics (HARM) code, which describes how spatial distributions of plasmas change near gravity regimes like a single black hole or neutron star. Noble modified the code to allow for two black holes to evolve.

Goddard and University of Maryland Assistant Research Scientist Bernard Kelly, who creates simulations using a different method than Noble, said scientists can also use a special approach called a moving puncture simulation. This approach accounts for the fact that scientists do not know what happens beyond a black hole's event horizon, but it also allows for more robust calculations than other simulations.

Moving puncture simulations allow scientists to avoid representing a singularity inside the event horizon — the part of the black hole from which nothing can escape. Everything outside of that event horizon evolves, while the objects inside remain frozen from earlier in the simulation. This allows scientists to overlook the fact that they do not know what happens within an event horizon.

As the simulations grow more realistic, scientists incorporated equations that describe how matter moves during a merger. Previous simulations essentially occurred in a vacuum, Kelly said, which could be simulated with just Einstein's equations. To mimic real-life situations, where black holes accumulate accretion disks of gas, dust, and diffuse matter, scientists have to incorporate additional code to track how the ionized material interacts with magnetic fields.

"If you want to follow what happens to plasma and other elements produced after a merger, that can take seconds, hours, or days to go through their

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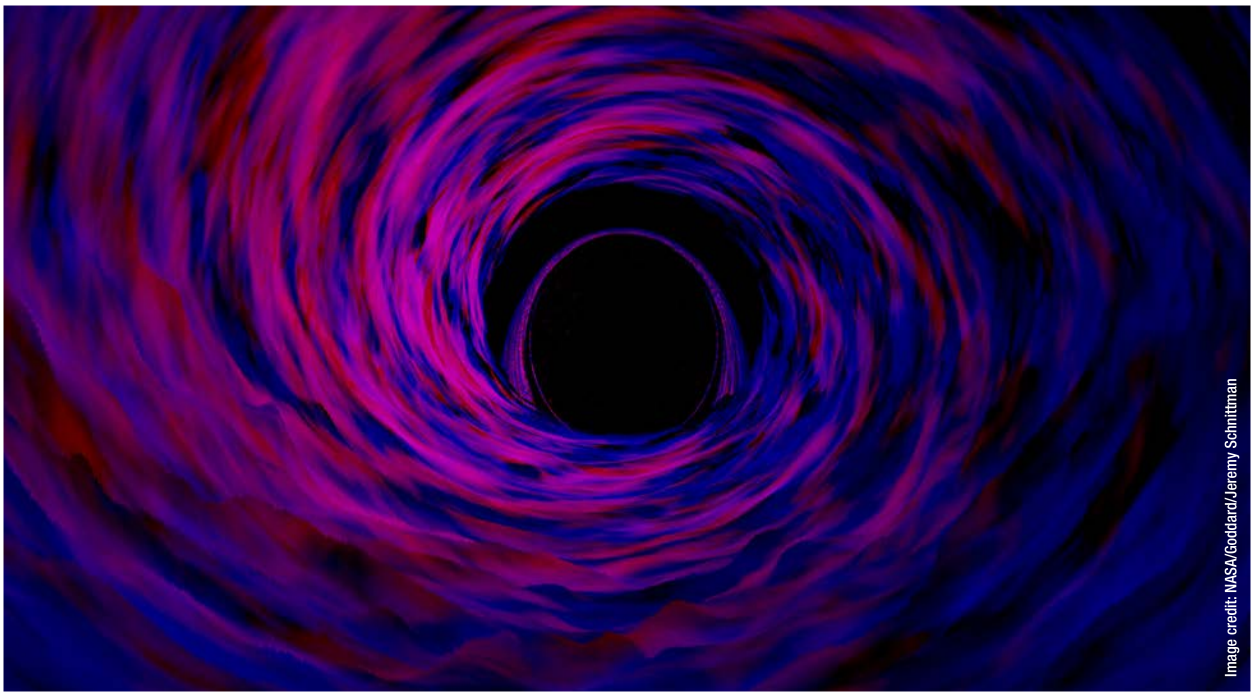

This visualization of supercomputer data shows the X-ray glow of the inner accretion disc of a black hole.

physical processes," Kelly said. "It's far too long using the codes we use. People are trying to use our numerical relativity code to create accurate mergers, then pass off this information to other codes. We're trying to seamlessly and correctly glue together different codes and simulation methods to produce one coherent picture."

The research team worked to make the simulations more realistic. In 2018, they published an analysis of a new simulation in The Astrophysical Journal that fully incorporated the physical effects of Einstein's general theory of relativity. The simulation established that the gas in the systems will glow predominantly in ultraviolet and X-ray light.

Simulations also showed that accretion disks in these systems are not completely smooth. A dense clump forms orbiting the binary, and every time a black hole sweeps close, it pulls off matter from the clump. That collision heats up the matter, producing a bright signal and creating an observable fluctuation of light.

While these simulations could be crucial for analyzing LISA's data, there are plenty of improvements to be made. Noble said they are currently working on adding what's called radiation coupling. Simulations assume that protons interact with electrons often enough that they quickly reach the same temperature, but electrons might cool faster than protons in some cases. Noble said the team hopes to address this issue by independently simulating both particle populations.

Scientists need not only to be confident in the simulations' accuracy, Goddard astrophysicist Jeremy Schnittman said, but they need to be able to apply the same simulation to a single black hole or a binary and show the similarities between the two systems.

"The simulation is going to tell us, we hope, what a smoking gun would look like," Schnittman said. "LISA is an antenna as opposed to a telescope, and we're going to hear something in the universe and get its basic direction, but nothing very precise. What we have to do is take our telescopes and look in that part of the sky, and the simulations are going to tell us what to look for to find a merging black hole."

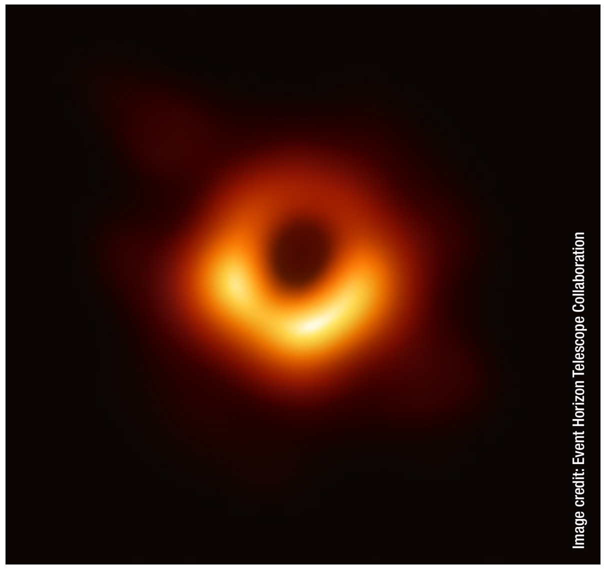
Image credit: Event Horizon Telescope Collaboration

The first image of a black hole shows the core of galaxy Messier 87 as resolved by radio waves by the Event Horizon Telescope in 2019.

Kelly said LISA will be more sensitive to lower gravitational wave frequencies than the current ground-based gravitational wave observer, the Laser Interferometer Gravitational-Wave Observatory (LIGO). That means LISA will be able to sense smaller events much earlier, and will likely detect merging systems in time to alert electromagnetic telescopes.

For Schnittman, these simulations are key to understanding the real-life data LISA and other spacecraft collect. The case for models may be even stronger for binary black holes, Schnittman said, because the scientific community has little data.

"We probably will never find a binary black hole with a telescope until we simulate them to the point we know exactly what we're looking for, because they're so far away, they're so tiny, you're going to see just one speck of light," Schnittman said. "We need to be able to look for that smoking gun." ❖

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Cutting edge Goddard's Emerging Technologies

CuttingEdge is published quarterly by the Office of the Chief Technologist at NASA's Goddard Space Flight Center in Greenbelt, Maryland. The publication describes the emerging, potentially transformative technologies that Goddard is pursuing to help NASA achieve its missions. For more information about Goddard technology, visit the website listed below or contact Chief Technologist Peter Hughes, Peter.M.Hughes@nasa.gov. If you wish to be placed on the publication's distribution list, contact Editor Karl Hille, Karl.B.Hille@nasa.gov. Contributors to this issue include Emma Edmund.

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