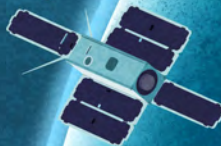
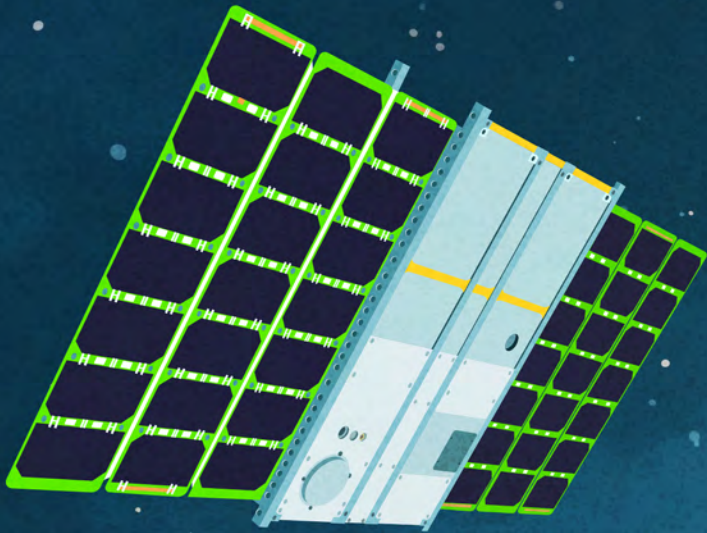


January/February 2019

Science & Technology

REVIEW



LIVERMORE'S CUBE SATELLITE EVOLUTION

Also in this issue:

Record-Breaking Neutron Yield
A Wolter Optic for X-Ray Imaging
Military Education and Outreach

About the Cover

The Laboratory's work developing small modular cube satellites, called CubeSats, applies innovative new technologies and is boosting the institution's space program. As the article beginning on p. 4 describes, Lawrence Livermore has been involved with CubeSat development for nearly a decade, which has resulted in enhanced optics and telescope designs and, more recently, the implementation of its own bus platform. Depicted on the cover is an artist's rendering of three Livermore-developed CubeSats in low-Earth orbit: (from top to bottom) MiniCarb, GEOstare-2, and STARE-A.



Cover design: Alexandria Diaz; Rendering: Ryan Goldsberry

About S&TR

At Lawrence Livermore National Laboratory, we focus on science and technology research to ensure our nation's security. We also apply that expertise to solve other important national problems in energy, bioscience, and the environment. Science & Technology Review is published eight times a year to communicate, to a broad audience, the Laboratory's scientific and technological accomplishments in fulfilling its primary missions. The publication's goal is to help readers understand these accomplishments and appreciate their value to the individual citizen, the nation, and the world.

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Prepared by LLNL under contract
DE-AC52-07NA27344

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S&TR, a Director's Office publication,
is produced by the Technical Information
Department under the direction of the
Office of Planning and Special Studies.

S&TR is available on the Web
at str.llnl.gov

Printed in the United States of America

Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

UCRL-TR-52000-19-1/2
Distribution Category UC-99
January/February 2019

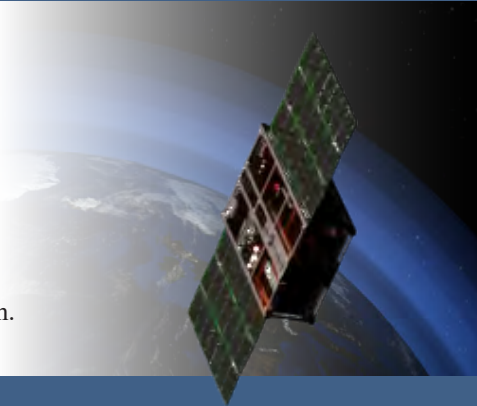
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SPACE PROGRAM ONE SMALL

A photograph showing three engineers in a cleanroom environment working on a satellite component. The engineers are wearing white protective suits, face masks, and safety glasses. They are focused on a complex piece of equipment, likely the laser heterodyne radiometer mentioned in the text. The background is dark with some faint lights, suggesting a laboratory or cleanroom setting. The overall scene is one of precision and technical expertise.

Engineers and scientists complete the installation of the laser heterodyne radiometer into the MiniCarb cube satellite, or CubeSat. Clockwise from bottom left is Lance Simms from Lawrence Livermore and AJ DiGregorio, Guru Ramu, and Jenny Young from NASA. (Not pictured: Emily Wilson, Darrell Carter, and Vincent Riot.) (Photo by Randy Wong.)

INNOVATION SATELLITE AT A TIME

The Laboratory's "out-of-this-world" technologies are enabling development of small modular cube satellites for space applications.

THE population of human-made satellites orbiting Earth has skyrocketed over the past 60 years. Launches nearly doubled from 2016 to 2017, and a significant contributor to this growth has been the development and implementation of small satellites that are easier and less expensive to build and more cost efficient to launch than conventional ones. Today, the hottest destination for these spacecraft is low-Earth orbit (LEO)—in the range of a few hundred kilometers above the planet's surface.

Nanosatellites, a class of small satellites weighing between 1 and 10 kilograms (kg), have become increasingly popular because of their lower cost and ease of construction—made possible through standardization. Cube satellites, called CubeSats, are a common type of nanosatellite comprising a modular framework of cube-shaped building block units (U) that measure 10 centimeters (cm) per side, about twice the size of a Rubik's cube. For comparison, the spherical Sputnik—the first artificial satellite in orbit—measured 58 cm in diameter and weighed 83.6 kg.

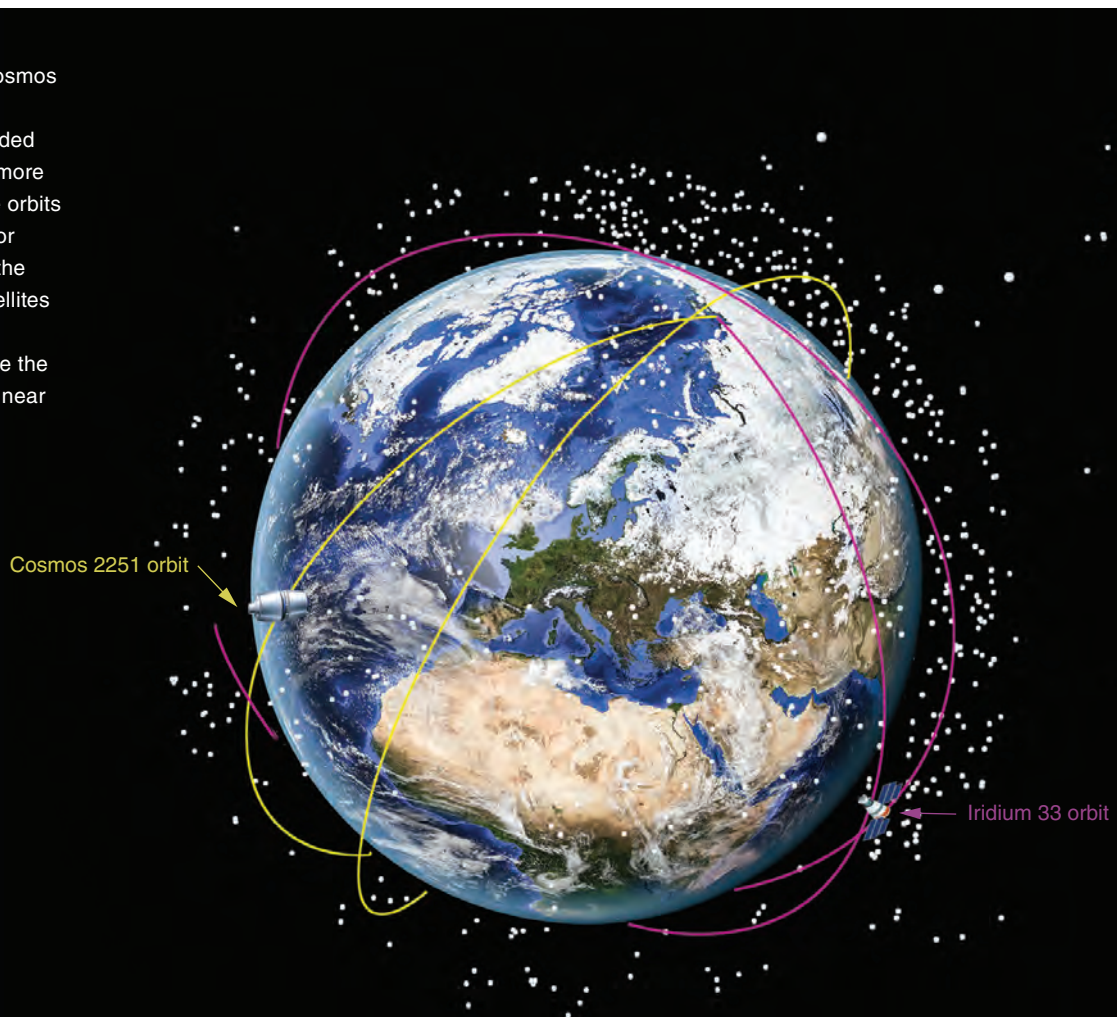
CubeSats typically comprise two main parts: a payload and a bus, the latter of which provides the structure, command and control, communication, power, navigation, and maneuvering systems for the spacecraft. Lawrence Livermore's first involvement with CubeSats was developing optical imaging payloads for the Space-Based Telescopes for the Actionable Refinement of Ephemeris (STARE) project to monitor space debris. (See *S&TR* April/May 2012, pp. 4–10.) Since then, the Laboratory has continued to advance CubeSat technology and strengthen the institution's space program. Through this work, Lawrence Livermore is embarking on new technological frontiers, from enhancing sophisticated optics and telescope designs to developing its own bus platform.

STARE-ing into Space

Consisting of derelict satellites, rocket boosters, and parts from spacecraft, pieces of space debris range in size from too small to be tracked to larger than a softball and can travel at speeds exceeding 25,000 kilometers per hour. Tens of thousands of these objects are tracked and considered lethal, and collisions, intercepts, and catastrophic failures continually increase the amount of debris. In 2009, for example, the inoperable Cosmos 2251 satellite collided with the privately owned Iridium 33 satellite over the Arctic at a closing speed of 12 km per second, breaking into more than 2,000 pieces of trackable debris. More recently, in 2015, astronauts aboard the International Space Station nearly collided with a fragment from a defunct weather satellite.

Though simple laws of physics govern the path of an orbiting object, variations in solar radiation and perturbations from the gravitational pull of the Sun, Moon, and Earth make determining the exact positions of any single object, let alone thousands, rather tricky. Satellites in LEO also experience drag from Earth's upper atmosphere. Ten years ago, a team from Livermore, consisting of engineers, physicists, and computer scientists, began studying how to improve detecting and tracking objects that threaten space operations. Funded by the Laboratory Directed Research and Development (LDRD) Program, their approach to space situational awareness (SSA) included using high-performance computing to analyze and simulate the trajectories of space debris and the results of hypervelocity collisions

In 2009, the defunct Cosmos 2251 satellite and the Iridium 33 satellite collided in Earth's orbit. A Livermore visualization shows the orbits of the two satellites prior to the collision among the thousands of other satellites in low-Earth orbit. The collision occurred where the two orbital paths cross near the North Pole.

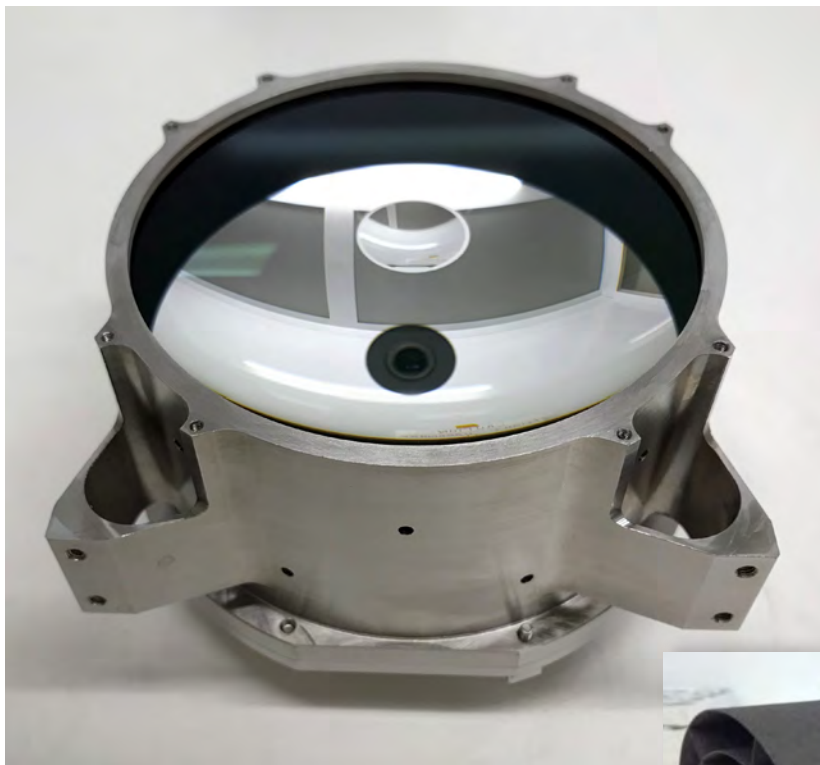


between satellites. The team applied improved orbital predictions with optical and radiofrequency observations to develop their model.

Building on this modeling effort, Livermore began a partnership to build a series of three CubeSats (STARE-A, -B, and -C) and launch them into LEO at approximately 700 km. The CubeSats were designed to investigate methods for better protecting operational satellites from fates similar to Iridium 33. Livermore was responsible for developing the telescopes as part of the optical imaging payloads. Each CubeSat telescope had a diameter of 8.5 cm, weighed less than 1 kg, and took up about 1U of space.

Whereas STARE-A and -B used a conventional telescope design with independent primary and secondary mirrors for viewing distant objects, the (unlaunched) STARE-C configuration was the first to feature a new monolithic optic, an approach that combines the primary and secondary mirrors into a single element. The idea stemmed from the dual-surface monolith that Livermore scientists helped develop for the Large Synoptic Survey Telescope. (See *S&TR*, September 2017, pp. 4–11.)

In 2014, a team led by Livermore physicist Wim de Vries partnered with the U.S. Air Force and commercial bus provider Tyvak to develop the 3U GEOstare-1 CubeSat. This satellite, and the subsequent GEOstare-2, also incorporated a monolithic telescope design and tested new concepts for SSA missions. Imagery of Earth and the Moon collected by GEOstare-1 during checkout operations validated the telescope's performance. "GEOstare-1 launched in January of

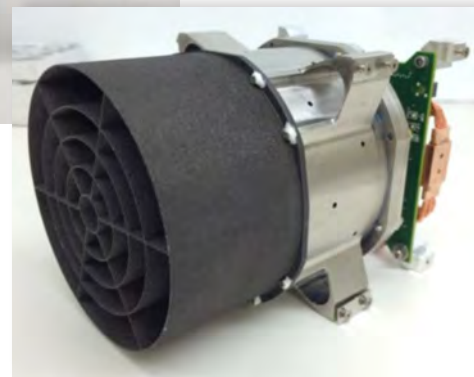


GEOstare CubeSats use monolithic telescopes, which combine the primary and secondary mirrors into a single optical element (left). The entire telescope assembly (below) also includes the baffle (black component) to reduce stray light.

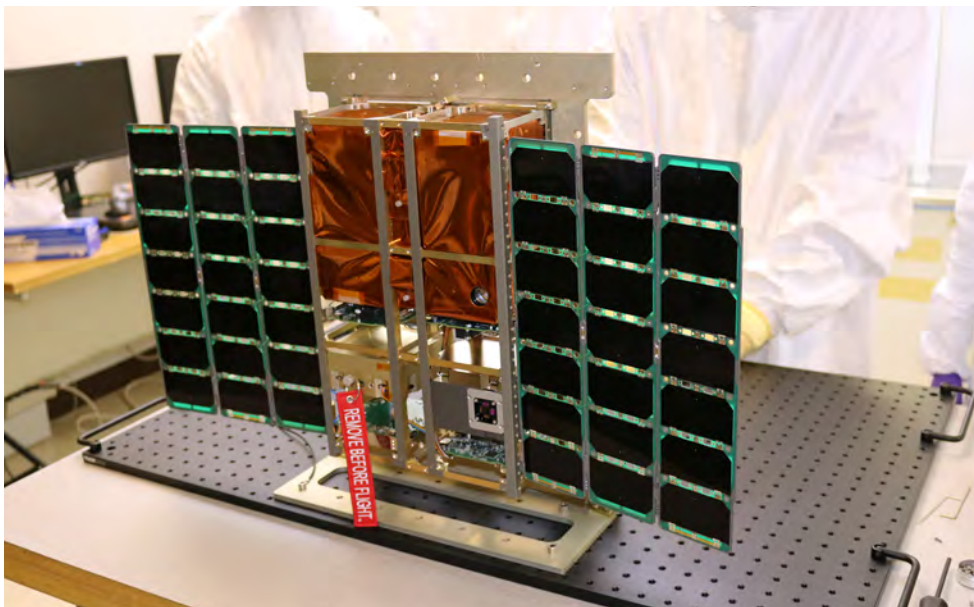
2018," says De Vries. "We're already done with the experiment, which produced beautiful data and validated all the ideas that we had." Scheduled to launch in 2019, GEOstare-2 is twice the size of its predecessor. The 6U CubeSat will carry a narrow-field-of-view color imager and a wide-field-of-view panchromatic imager mounted side-by-side to fulfill its SSA mission.

Building a Next-Generation Bus

Once in orbit, bus failures prevented both STARE-A and STARE-B from becoming operational, so neither could be evaluated in space. Instead of launching STARE-C to space, the partners moved in new directions. Livermore again focused on telescope payloads but also began work on a new bus design. In 2014, a team led by Livermore engineer Vincent Riot, in collaboration with colleagues at the Naval Postgraduate



School and under sponsorship from the National Reconnaissance Office, created the CubeSat Next Generation Bus (CNGB) architecture. The bus design featured flexibility; transparency; and mechanical, electrical, and software standardization. Though initially defined for a 3U CubeSat, CNGB is scalable to larger configurations. Darrell Carter, lead Livermore mechanical designer for CNGB, notes, "We used the lessons learned from STARE-A and STARE-B to guide our designs and ensure we could easily and reliably mount, test, and unmount components as needed."



MiniCarb combines NASA's laser heterodyne radiometer (seen in orange) and Livermore's CubeSat Next-Generation Bus, which consists of all the other components. (Photo by Dan Linehan.)



During a telemetry verification test of MiniCarb's satellite radio, physicist and engineer Lance Simms (right) and engineering summer student Nicholas Hsiao send a communication signal to the Iridium satellite network in space. The signal is relayed back to them via a ground station. (Photo by Dan Linehan.)

To provide the most design flexibility and efficient integration of payloads, the framelike structure—a lattice reminiscent of an Erector Set toy—was designed with 4 perforated rails running the length of the CNGB structure. The rails are fastened together by 16 crossbars, and the payload and other components mount to these rails. The widely used vehicle Controller Area Network (CAN) interface handles the electricity and data signals. To support a broad range of computing platforms, the bus includes the Space Plug-and-play Avionics (SPA) software interface.

“This work represents the building blocks for one sector of the Laboratory's space program,” says Bill Bruner, a senior advisor for Livermore's Space Science and Security Program (SSSP). “For years we have built instruments and optics for others. Now, thanks to a boost from our work with the National Reconnaissance Office, we are also providing bus platforms that can deliver different services for sponsors depending upon their needs.”

Introducing MiniCarb

With the new Livermore bus design in place, in 2016 the team began partnering with NASA Goddard Space Flight Center to develop the payload and the U.S. Air Force to provide a way to launch the spacecraft. Using CNGB, the final size of the CubeSat, called MiniCarb, is 6U. Once in orbit at 500 km, MiniCarb will be used to monitor atmospheric gases. “This work represents the first time that we are launching a Livermore-developed spacecraft,” says Riot, who also leads Livermore's MiniCarb team. “It's a proof of concept for our bus design, but we are also conducting important science with a NASA payload.”

Building satellites inexpensively requires an innovative approach. MiniCarb was built for only \$500,000 by using commercial parts that have limited lifespans in the harsh environment of space. Costs were further managed by

assembling the satellite under a clean hood as opposed to in a clean room. Some of the prelaunch testing even occurred outdoors. Says Riot, “It’s a cost–schedule–performance tradeoff.” CNGB has realized the goal of cost efficiency whereby a second one would only cost a few hundred thousand dollars more to produce, take a year to build with minor modifications, and incorporate upgraded technologies and capabilities. Quick iteration of the “design–build–test–fly” cycle is the key to obtaining performance and reliability.

As with other CubeSats, MiniCarb relies on GPS and star tracking to determine its exact location and orientation. Similar to other modern satellites, MiniCarb rotates around and refines its aim using three continuously spinning reaction wheels.

Power is generated by two trifold solar panels, stored in 6 lithium batteries, and delivered by a software-controlled distribution system. This entire power system is one of Lawrence Livermore’s key innovations for CubeSats. For data transmission and other telemetry, MiniCarb uses a modem from Iridium Communications, Inc., to connect to the company’s network of satellites in orbit. In seconds, the network relays communications back and forth to an Iridium ground station linked to Livermore’s spaceflight control center.

To ensure MiniCarb can withstand the various hazards in orbit and promote its successful operation, all systems are tested and verified prior to launch as part of NASA’s Technical Standards Program. To help the satellite survive the harsh space environment, a bright, coppery-orange thermal blanket regulates the payload’s temperature as MiniCarb’s orbit causes a swing from 5°C to 45°C.

MiniCarb on a Mission

On May 8, 2018, NASA installed a 4U laser heterodyne radiometer (LHR)

A Spacefaring Coast Guard

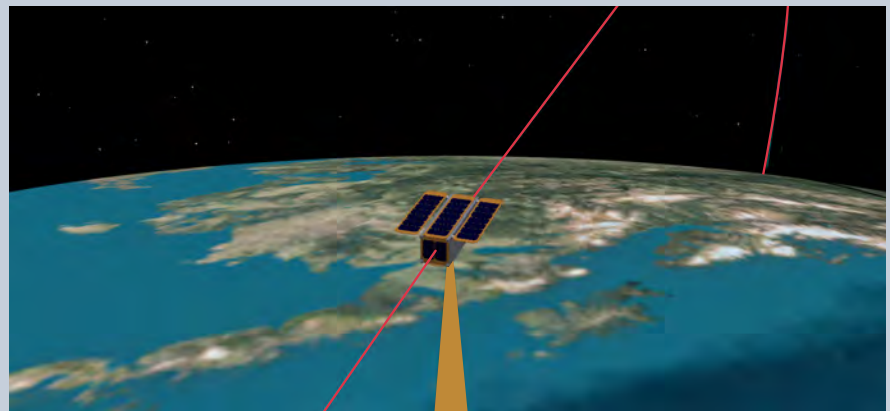
Nanosatellite technology, in particular, small cube satellites, are finding purpose in the most extraordinary places. Known as CubeSats, these miniature versions of conventional satellites can be used for applications that range from tracking space debris to monitoring atmospheric gas concentrations. Now, Lawrence Livermore scientists and engineers are turning their expertise in CubeSat development toward assisting the U.S. Coast Guard in becoming a spacefaring agency.

Shawn Higbee, an associate program leader in the Laboratory’s Space Science and Security Program, leads the project. He says, “The Coast Guard came to us because they were excited by the promise of space and wanted to refine their strategy on where to start. So, we helped develop a strategy and technical roadmap for how small satellites could help Coast Guard missions.”

With more than a dozen mission objectives, which include search and rescue activities, iceberg monitoring operations, law enforcement, fishery protection, and homeland defense, the Coast Guard operates over vast areas of the Arctic, Pacific, and Atlantic oceans. The rigorous demands across this remote expanse present many challenges for the Coast Guard. For example, the melting of the Arctic ice sheet and the opening of the Northwest passage have provided an avenue by which ships can now travel ocean to ocean. The lack of infrastructure in the Arctic and the increasing risks have the Coast Guard looking to CubeSats as a way of protecting these new waterways.

In 2018, two 3U CubeSat payload prototypes were developed at the Laboratory and delivered to the Coast Guard Academy for education and training. The devices are to be used by academy cadets for instructional purposes on dry land as the Coast Guard begins its journey with space technology. The prototypes are designed for maritime domain awareness missions, but one specializes in searching for life rafts adrift in the ocean. The distinct orange color of life rafts makes it easy for the CubeSat to identify them against a backdrop of seawater.

The Coast Guard is interested in CubeSats as a cost-effective approach to improving the performance of many missions. Another advantage of having its own fleet is that it allows the Coast Guard to more easily share information with international partners and use it for law enforcement proceedings.



This simulation shows a U.S. Coast Guard CubeSat in orbit over Alaska’s Aleutian Peninsula searching for life rafts after a storm.

into Livermore's CNGB to complete the MiniCarb CubeSat. By collecting sunlight that has passed through slices of Earth's upper troposphere and lower stratosphere, LHR can detect the amount of sunlight absorbed by methane (CH₄) and carbon dioxide (CO₂). Absorption spectra are then used by scientists to measure the concentrations of these greenhouse gases.

For LHR to work, it must mix the incoming sunlight with laser light of a wavelength that corresponds to the absorption peaks of the gases. Advancements in technology and the increasing availability of laser components enabled the design of an existing ground-based LHR to be miniaturized for use in MiniCarb. The key to the LHR instrument development was finding the solid-state, distributive feedback laser tunable to around 1,640 nanometers.

Unlike typical ground-based LHRs that cannot distinguish between gas concentrations at different altitudes, or current remote-sensing, atmospheric satellites that point directly to the ground,

MiniCarb will have a better vantage point. With the atmosphere positioned between a direct line of sight from the Sun to MiniCarb, the orbiting LHR can take multiple measurements as the CubeSat orbits. Each measurement slices through a different altitude, providing key details about the concentrations of greenhouse gases within the atmosphere.

The launch of MiniCarb will mark the first time an LHR enters space and the first use of a CubeSat to measure CH₄ and CO₂ simultaneously. NASA scientist Emily Wilson leads the LHR design and MiniCarb's science mission. She says, "Compared to other types of commercial instruments, LHR gives a better-quality measurement because of its higher spectral resolution." Favorable angles occur twice per orbit—the best measurement positions occur during sunrise and sunset from the CubeSat's point of view. MiniCarb must rotate between observations at these two positions. MiniCarb records two series of scans each time it circles Earth. Up to five scans are completed per position, with each

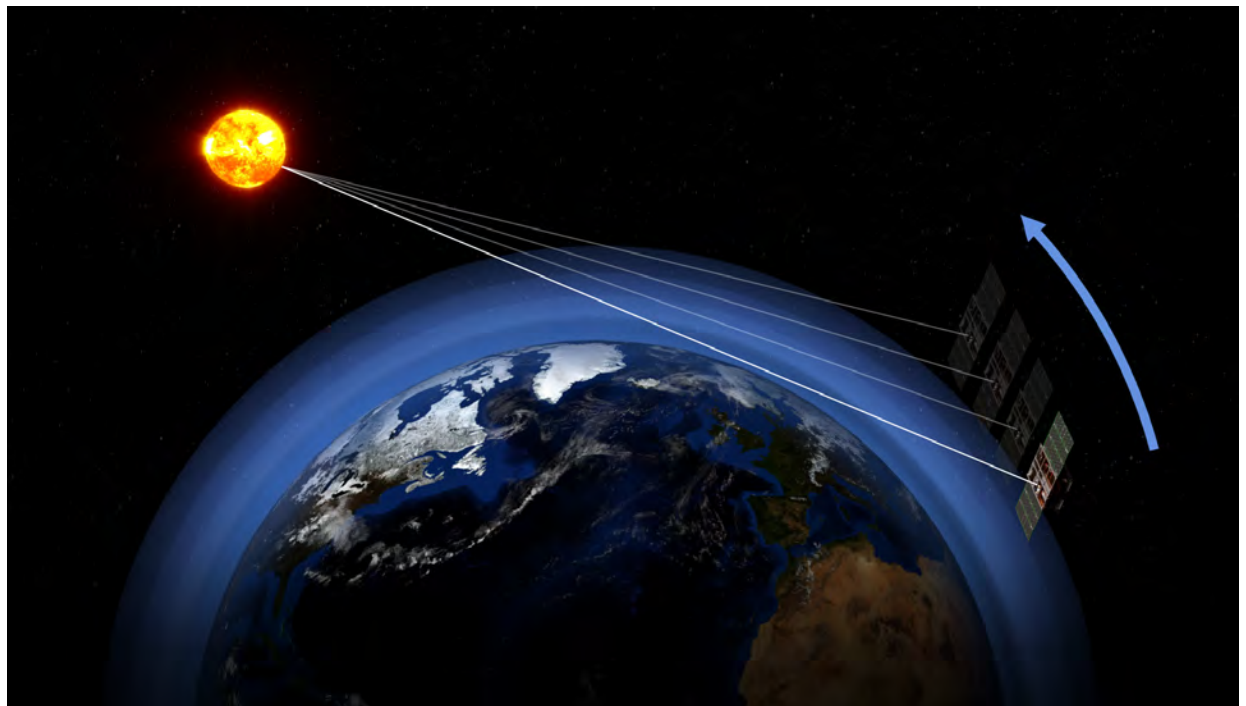
scan lasting about a minute and collecting approximately a hundred data points.

After MiniCarb's three-month mission, its orbit will naturally decay over about two years and then burn up in Earth's atmosphere so as not to add to the collection of already defunct satellites in space. Of the approximately 4,800 satellites in orbit, less than half of them are operational.

Small Satellites, Big Potential

The successful launch of MiniCarb will mark the first time a CubeSat bus built by the Laboratory is delivered to space. It will also represent the maiden voyage and operation of NASA's innovative LHR instrument. Scheduled for no earlier than May 2019, MiniCarb will be put into space by a commercial launch provider as part of an Earth-to-orbit rideshare. It will be an Air Force Space Test Program mission launched by VOX Space on the Virgin Orbit LauncherOne vehicle. Based in Southern California, launch providers VOX Space and Virgin Orbit are subsidiaries of

This artist's rendering shows the direct line of sight between the Sun and MiniCarb, which will be used to monitor atmospheric gases. (Rendering by Jacob Long.)





Virgin Orbit's LauncherOne rocket, which blasts off after dropping from underneath the wing of a modified 747, will take MiniCarb into orbit with several other satellites. (Image courtesy of Virgin Orbit.)

Virgin Galactic. Such partnerships make splitting the cost for a ride to space much more affordable.

Branching out with new mission concepts, improved optical payloads, and other technological advances, CubeSat projects contribute to both basic science and national security endeavors and have helped shape the broader Laboratory space program and mission. (See the box on p. 9.) Mike Pivovarov, the program leader for SSSP, adds, “The Laboratory’s strength is looking at a sponsor’s mission, separating it into basic requirements, and then doing the architectural studies, which regularly require high-performance computing. The focus of our integrated team is to provide a cost-effective

solution for getting the best data for the sponsor.”

The research and development efforts have also enabled Livermore to expand its space technology expertise, which can be further applied to existing programs at the Laboratory. “For example, what if our additive manufacturing group produces a breakthrough structural element that can be used as an antenna, and scientists want to fly the element to space because it supports underlying missions,” says Pivovarov. “We are now in a position to bring these efforts together in a vertically integrated way.”

Through a strong understanding of the principles that guide operations in orbit, development of innovative instruments,

and research and design that promotes the realization of more cost-effective spacecraft, Livermore’s space program is embarking on something extraordinary. CubeSat by CubeSat, the Laboratory is demonstrating that small modular satellites are just the beginning of big scientific breakthroughs.

—Dan Linehan

Key Words: bus, cube satellite, CubeSat, CubeSat Next Generation Bus (CNGB), GEOstare, Large Synoptic Survey Telescope, laser heterodyne radiometer (LHR), LauncherOne, MiniCarb, monolithic telescope, nanosatellite, payload, Space-Based Telescopes for the Actionable Refinement of Ephemeris (STARE), space debris, Space Science and Security Program (SSSP), space situational awareness (SSA), telescope.

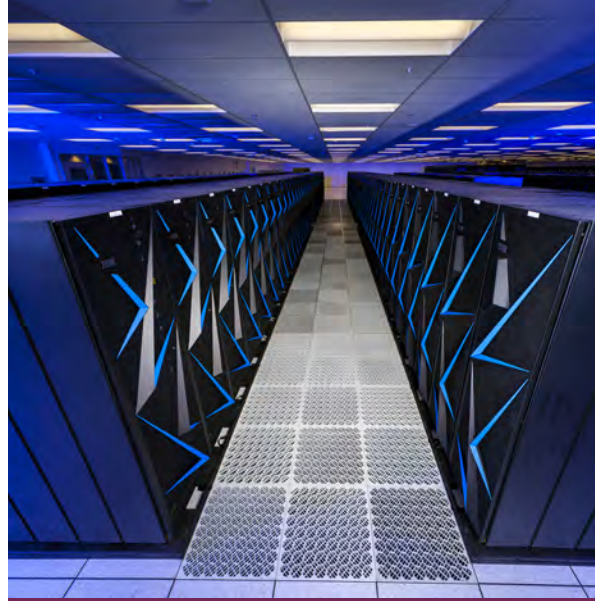
For further information contact Vincent Riot (925) 422-9798 (riot1@llnl.gov).

Space Program Innovation, One Small Satellite at a Time

Cube satellites, called CubeSats, are a common type of nanosatellite comprising a modular framework of cube-shaped building block units that measure 10 centimeters per side. Their lower cost and ease of construction compared to large, conventional satellites have made them a popular choice for modern space applications. Lawrence Livermore's first involvement with CubeSats began nearly a decade ago when scientists developed optical imaging payloads for the Space-Based Telescopes for the Actionable Refinement of Ephemeris project to monitor space debris. More recently, as part of a collaboration with NASA Goddard Space Flight Center, the Laboratory has helped develop the MiniCarb CubeSat for measuring atmospheric greenhouse gases. MiniCarb will be the first to use the innovative, Laboratory-developed CubeSat Next Generation Bus platform, ushering in a new era for the institution's Space Science and Security Program.

Contact: Vincent Riot (925) 422-9798 (riot1@llnl.gov).

Machine Learning on a Mission



Livermore's innovative data-driven techniques teach computers to solve real-world problems.

Also in Month

- *At a new Laboratory facility, scientists and industry colleagues work side by side to supercharge the nation's manufacturing capability.*
- *Nanolipoprotein particles may deliver a safe and effective vaccine for one of the most infectious bacterial pathogens in existence.*
- *Three-dimensional images enhance understanding of cracks in superalloys.*