UPWARD

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ISS NATIONAL LABORATORY®

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ISS NATIONAL LABORATORY®

VIEW FROM THE CUPOLA

BY EMILY TOMLIN, Former Associate Director For Communications, CASIS

Originally published February 26, 2021

In February 2016, we released our first issue of *Upward*, official magazine of the International Space Station (ISS) National Laboratory. It was a labor of love.

Looking back, it is amusing to think that in the early stages of planning, the initiative was going to be a newsletter. However, as our small team of scientists and science writers began conceptualizing the format and content, we saw a great need for feature-length articles to showcase the incredible results coming out of the ISS National Lab. Our first issue had three such features and four "spotlights," shorter stories that were not always focused on results alone. In our inaugural issue and each publication since, we also lead off with a "Perspective," or an opinion-style contribution that later became the one place we allowed guest contributors to lend their voice to the magazine.

We have covered results from Fortune 500 companies, small startups, research universities, and educational organizations—spanning life and physical sciences, remote sensing, technology development, and more diverse science topics. The theme, however, was constant: Space is enabling out-of-this-world research and development (R&D) that benefits life back on Earth.

How Does Space Benefit Life on Earth?

It is intuitive that the impacts of microgravity on biological and physical systems are critical to understand if we are to reach the lofty NASA goals of Artemis (returning astronauts to the lunar surface by 2024) and beyond. Perhaps less obvious is the value of understanding these impacts in pursuit of knowledge generation and translational science that seeks to improve healthcare and consumer products on Earth.

Inside the station, humans and objects float in the weightlessness of microgravity—minimal gravitational pull with minor "jitters" from spaceflight. These conditions have dramatic effects on the biological and physical systems that have evolved in and been studied for centuries on Earth. Everything from cell biology to fluid physics is altered, providing an opportunity for scientists to treat gravity itself as a variable in simple to complex scientific investigations that aim to improve not only humanity's capability to explore the depths of space but also the quality of human life here on Earth.

Additionally, outside the station in the extreme environment of low Earth orbit (LEO—not to be confused with "outer space," as it is only a mere 250 miles above the Earth's surface!), one can encounter high-energy radiation, extreme vacuum conditions, tremendous fluctuations in temperature, and other conditions that simultaneously stress systems and materials placed in R&D facilities mounted to the station. Moreover, the view of Earth from above, flying in a 17,500-mph orbit that covers 90% of Earth's inhabited surface, provides a unique vantage point from which to image and study Earth's surface and atmosphere, including the real-time monitoring of natural disasters.

While the treasure trove of scientific opportunity in space has been used by scientists for decades, the ISS has only somewhat recently (about 10 years now) been managed in part by the Center for the Advancement of Science in Space™ (CASIS™). At CASIS, we facilitate access to the ISS National Lab as a public service to the nation, advancing U.S. leadership in commercial space, fostering science and innovation in microgravity, and inspiring the next generation. Because of the ISS National Lab, the research, results, and stories behind the past 10 years of R&D in space are evolving toward a more democratized landscape—and we were well poised to share that narrative through authentic storytelling.

And so we did! Moreover, we made a commitment to journalistic and scientific integrity in developing the stories, covering the scientific and technological achievements of our projects without trying to "sell" the value of the ISS for R&D. I used to joke that our goal was to make this one product purely "communication without the marketing." Another team member also labeled it well: "This is where we make our researchers rock stars." I hope both those things have held true and continue to hold true in the years to come.

It has been such a joy to work on *Upward*, diving deep into all the amazing science happening in space today—and exploring the human faces and stories behind the research. I am proud of the team that built the magazine (including our freelance and intern contributors), thankful to the management that allowed us to grow and nurture it, and grateful to all those who let us interview, photograph, and immortalize them within its pages.

Finally, thank you to our readers. Without you, our team would be lost in a sea of stories without anyone to share them with. You are the motivation and inspiration for us to continue to aspire ever *Upward*. I hope you enjoy exploring this compilation of stories.

A Note From *Upward* Managing Editor, Amelia Williamson Smith

This special compilation issue features a collection of *Upward* articles that were published online between 2020 and 2022 but were never included in an issue. The articles have been slightly modified from their original published form for inclusion in this compilation. I hope you enjoy reading about the many ways in which results from these ISS National Lab-sponsored investigations are benefiting humanity and providing value to our nation.

Crystal Clear

Super-Sized Protein Crystals From Space Could Help Treat Diseases On Earth

BY STEPHENIE LIVINGSTON, *Staff Writer*

Originally published
July 26, 2022

In Greek mythology, Pandora's Box releases disease and other miseries into the world. But in real life, a very different type of box uses microgravity to do the opposite: fight disease back on Earth.

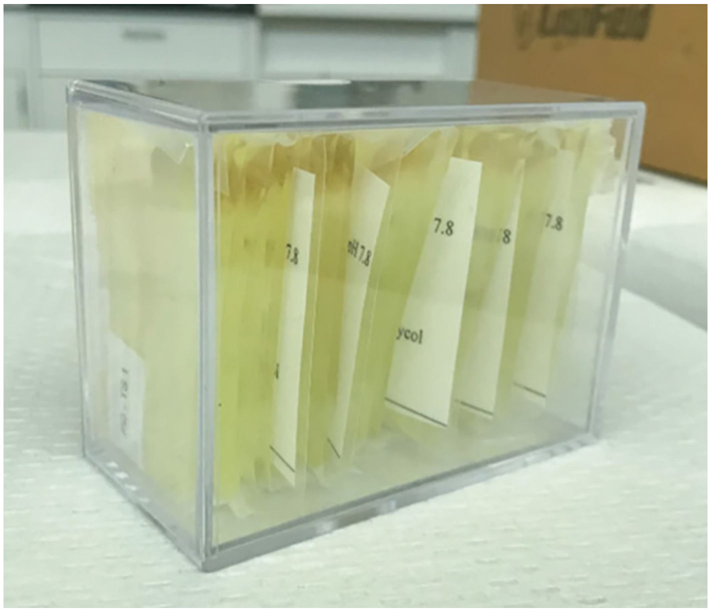
University of Toledo biochemist Timothy Mueser's "Toledo Crystallization Box" utilizes the microgravity environment of the International Space Station (ISS) to change the physical form of proteins involved in human disease into large crystals. Such crystals can provide new data about the physical structure of proteins that can offer insights into their function—information essential to developing new pharmaceutical drugs to help patients.

Using protein crystals grown in the Toledo Crystallization Box during an ISS National Laboratory®-sponsored investigation, Mueser and his colleagues did something that had never been achieved on Earth. Using neutron diffraction, the team pieced together the structure of bacteria-derived tryptophan synthase (TS), a key enzyme involved in the ability of salmonella and other bacteria to cause infection. This represents the first time researchers have directly visualized the position of protons within vital functional elements of the enzyme's structure, allowing Mueser's team to develop physical models of the enzyme that are more accurate than ever before.

European Space Agency astronaut Alexander Gerst places Toledo Crystallization Boxes (TCBs) into storage onboard the ISS.

NASA

Knowledge of this atomic-level structure aids in developing antibiotics that better target and inhibit bacterial pathogens, said Mueser, a professor of chemistry and biochemistry at the University of Toledo's College of Natural Sciences and Mathematics. His team's space-based experiment is detailed in a study recently published in the journal npj Microgravity.



A filled Toledo Crystallization Box containing 50 individual crystallization experiments.

NPJ Microgravity

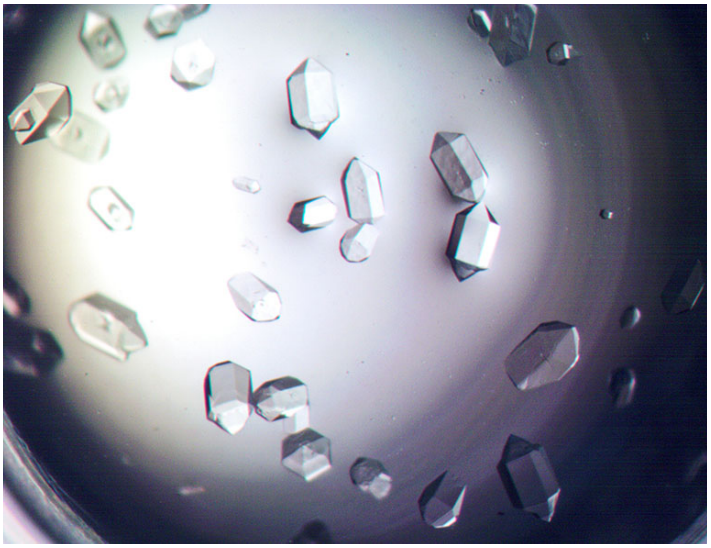
To achieve the neutron structure for TS, microgravity was vital. On Earth, some proteins crystallize with inclusions and high mosaicity (misalignment within the crystal lattice during the crystal's growth) that create imperfections in the physical image of the structure. However, in microgravity, crystals form in a sort of slow-motion—the absence of gravity-driven convection allows proteins to crystalize slowly and often more orderly. For some proteins, like TS, this results in bigger crystals than can be achieved on Earth.

"The crystals were beautiful—we got exactly what we were after," Mueser said. "We had no way of getting those crystals without that microgravity flight."

Microgravity as a Magnifying Glass

In the same way that we use visible light captured by cameras to observe details in pictures, scientists observe protein crystals at an atomic level by using X-ray or neutron diffraction to pinpoint the physical position of atoms in the protein. Such structural data can be used to uncover new targets for drug development. Traditional structure-based drug design uses 3D models created via X-ray diffraction, but these models sometimes have incomplete structural data or lack detail. Neutron diffraction, unlike X-ray diffraction, reveals the position of hydrogen atoms, which make up around 50 percent of the atoms in proteins and are missed by X-ray diffraction.

The public Protein Data Bank holds more than 100,000 protein structures, but less than 100 have neutron diffraction data. When drugs are designed against incomplete protein structures, the wrong targets can be identified, leading to serious side effects.



Aeropyrum pernix Flap Endonuclease-1 (FEN-1) protein crystals grown under Earth gravity conditions are shown. While impressive, these crystals from a past experiment by Timothy Mueser's lab are smaller and of less quality than those his team grew during their most recent experiments onboard the ISS.

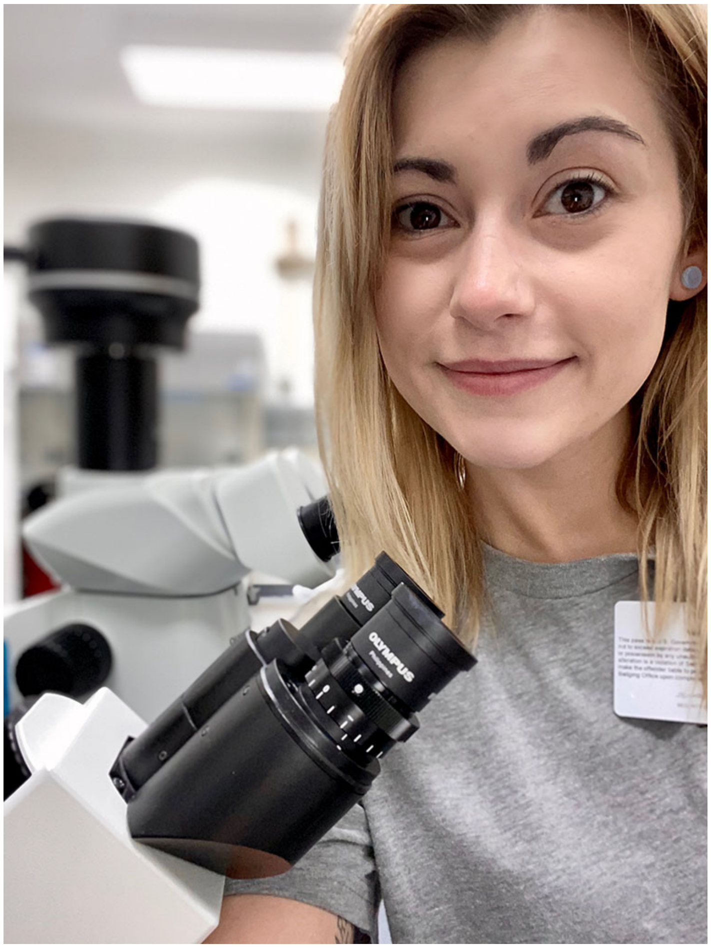
University of Toledo

The challenge is that for neutron diffraction to work, you need crystals that are well-ordered and large—about 100 times bigger than the crystals typically used for X-ray diffraction. This can be difficult to achieve on Earth, as it can take years to identify the best conditions for the crystals to grow, and the crystal quality may not be high enough for neutron diffraction. Microgravity provides a solution for quickly growing large, high-quality crystals for some proteins. For this reason, Mueser and his team took their protein crystallization to space.

Mueser's 2019 ISS investigation is part of an ongoing evolution of molecular crystallization studies using microgravity that spans decades. "It's pretty exciting," Mueser said. "This work really started with the flight of the first protein crystallization experiment way back in the day."

Probing Proteins for Targeted Drug Development

When the team's experiment launched on SpaceX's 18th Commercial Resupply Services (CRS) mission, it contained three enzymes (proteins that act as catalysts in biological processes) specifically picked for their dependence upon vitamin B6-derived pyridoxal 5′-phosphate (PLP). The three were: Salmonella typhimurium tryptophan synthase (a complex of tryptophan synthase from the bacterial pathogen salmonella), another protein related to heart and liver disease, and a complex of two proteins involved in DNA repair.



Biochemist Victoria Drago examines protein crystals under a microscope.

Victoria Drago

Mueser's team is interested in PLP-dependent enzymes because they are common to many organisms in all branches of life and are part of a diverse family of enzymes responsible for more than 100 different chemical reactions in cells. Despite their prevalence and importance, the relationship between the structure and function of the enzymes is poorly understood. Researchers need to see the enzymes in their entirety on an atomic level to complete their structure and understand how they function.

Because bacterial-derived TS is involved in the metabolic processes of many different microorganisms, it is a model enzyme for understanding PLP-dependent enzymes. This, coupled with the fact that TS does not occur naturally in humans, makes it a common target for drugs designed to inhibit human pathogens that depend on it, including infections caused by salmonella and staphylococcus (staph infection).

"While our team doesn't focus on eliminating salmonella, we want to figure out how we can intervene via PLP-dependent enzymes," said biochemist Victoria Drago, a recent Ph.D. recipient from Mueser's lab who led the team's investigation on the ISS. "Our primary goal is to understand PLP and how it is modulated by PLP-dependent enzymes to be so versatile."

If you do not understand the action occurring inside the enzyme, it is difficult to inhibit it, Drago explained. In an infection propelled by PLP-dependent enzymes, one of the steps involves the enzyme's hydrogen atoms being shuffled around during a reaction. Thus, understanding where the hydrogen atoms are and how they move inside the enzyme is essential to designing targeted antibiotics, she said.

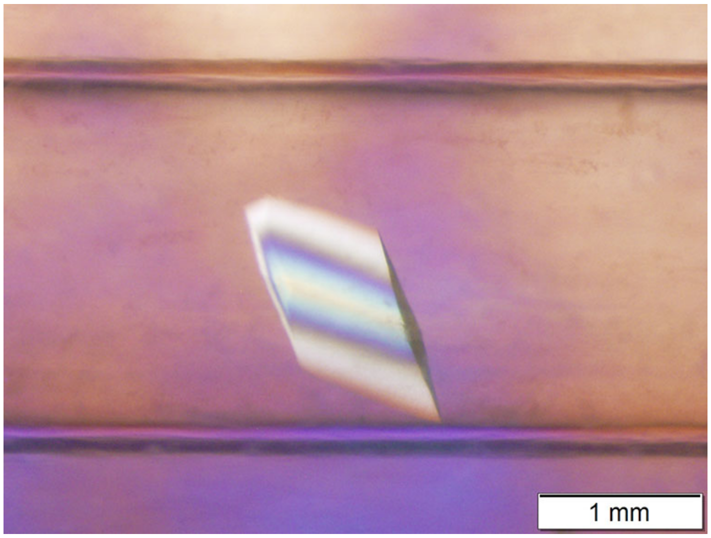
A complete neutron structure for TS could lead to better-targeted drugs to treat infections driven by PLP-dependent enzymes, such as salmonella infection, which affects about 1.35 million people in the United States each year. "It is possible salmonella could be thwarted in its growth if you could reduce its ability to get tryptophan, resulting in less severe illness or no illness at all," Drago said.

Neutron Diffraction in Pandemic Times

The team's ISS investigation consisted of three Toledo Crystallization Boxes—one for each enzyme. Inside each box sat 45 to 50 quartz capillaries containing protein solutions, sealed on one end with beeswax and the other with a permeable membrane. These capillaries were put inside a small bag that included a crystallization solution that slowly diffuses over several months to form crystals. After launching in 2019, the boxes sat tightly packed and untouched in a locker on the ISS for six months while the crystals formed.

The investigation returned to Earth on SpaceX CRS-19 in January 2020 amid a looming global pandemic. Mueser and the team were eager to assess the quality of the crystals and were a little nervous. They knew things go wrong in experimentation. Sometimes protein crystals that are hard to grow in gravity conditions also fail to grow in microgravity. Capillaries can break. Protein solutions can go wrong.

After the capsule splashed down in the Pacific Ocean and samples were shipped to Texas, Mueser picked up the experiment at NASA's Johnson Space Center in Houston. When he opened the Toledo Crystallization Boxes, he found more than 150 crystals distributed among the capillaries in the three boxes. Crystals of aspartate aminotransferase—a protein related to heart and liver disease—in the first box were the perfect size for the team's planned X-ray diffraction studies. The second box contained two DNA repair proteins that form a transient complex, but only remnants of crystals were found. For these two proteins, it is not easy to grow large crystals on Earth or in space. However, the crystals in the third box, which contained deuterated TS, were different. In that box, there were near-perfect, super-sized (>1 mm3) crystals. The team was thrilled.



Microgravity-grown crystal of perdeuterated tryptophan synthase (TS) for neutron diffraction.

Victoria Drago

Mueser flew with some of the crystals to the Oak Ridge National Laboratory in Tennessee, where the Spallation Neutron Source (SNS) facility and the High Flux Isotope Reactor (HFIR) are maintained by the U.S. Department of Energy. The HFIR facility allowed the team to begin their data collection using neutron diffraction, although Mueser saved the largest, highest-quality crystals for neutron diffraction at Institute Laue-Langevin in Grenoble, France. This lab houses another nuclear reactor, and his colleagues there had expressed the protein in heavy water to make it more amenable to neutron diffraction studies. However, by this time, the COVID-19 pandemic was well underway, and travel restrictions prevented him from delivering the crystals in person as he typically would. So, Mueser decided to take a risk.

He again tightly packed the hard-earned crystals in bubble wrap and tape and placed them in a box—but this time, it was a FedEx box. The experiments had traveled almost 50 million miles in low Earth orbit, but the last 3,000 miles back on the ground would be the most precarious.

Luckily, the crystals made it to France intact. But due to delays caused by the pandemic, Muesser's colleagues in the hard-hit South of France took more than a year to finish neutron diffraction and data collection for the TS crystals. As data finally poured in from Grenoble, Drago began piecing together the atomic-level images to form the first neutron structure of TS. "For the first time, it's all there for your eyes to see," said Drago.

She is studying the structure and developing more accurate models for understanding how PLP influences the enzyme's reaction and role in salmonella and other pathogens. These structural models may also be used more broadly for the general study of PLP-dependent enzymes because TS is a model for many of them.

Designing the Toledo Crystallization Box

Several devices for growing protein crystals have flown in space since the 1980s, but they were for short-duration experiments and were not designed to grow large crystals for neutron diffraction. Over the past 15 years, access to long-term microgravity on the ISS has led to advancements in this type of space-based crystal growth. Additionally, as the availability of neutron beams at research centers emerged, so has a new priority among molecular crystallization researchers to develop devices made explicitly for growing large crystals for neutron diffraction.

Early Space-Based Crystallization for Neutron Diffraction

The first investigators to grow neutron diffraction-quality crystals using the GCB on the ISS were from the University of Alabama and included Joseph Ng, a biochemistry professor at the University of Alabama in Huntsville. Ng said the Toledo Crystallization Box is a suitable replacement for the GCB to grow crystals big enough for neutron diffraction by counter-diffusion equilibration. Insight gained from the analysis of such microgravity-grown crystals could lead to valuable advancements in drug design.

"Three-dimensional structures of proteins deciphered by neutron crystallography can provide atomic details that cannot be obtained by X-ray crystallography alone," Ng said. "The accuracy of knowing the atomic spatial arrangement is critical for structure-based drug discovery processes."

Mueser designed the Toledo Crystallization Box to perform a very slow, diffusion-controlled crystallization in microgravity. His team based the design on a previous NASA-approved device, the "Granada Crystallization Box" (GCB) developed and sold by Triana Science and Technology in Granada, Spain for salt-based counter-diffusion. Mueser and his team named their new device the "Toledo Crystallization Box" (TCB) in homage to the GCB. However, the Toledo Crystallization Box is different because it allows broader crystallization conditions and has a more cost-effective off-the-shelf design.

The Toledo Crystallization Box (TCB) shown here is packed with 50 individual crystallization experiments and ready for flight.

Victoria Drago

"Our box is simple," Mueser said. "It's about $100 worth of material wrapped in bubble wrap and mylar tape."

The Toledo Crystallization Box has been tested twice on the ISS, most recently in the team's 2019 investigation, and the resulting TS crystals demonstrated that it can successfully yield "beautiful, super-sized" crystals for neutron diffraction, Mueser said. Now that its success has been demonstrated, the team plans to use the Toledo Crystallization Box for future ISS experiments, including those by other labs. Drago said, "Sending our device back to the ISS in the future, packed with our experiments and experiments from others, is definitely something we hope for and that we're working toward."

For Mueser, the path forward is a progression of his life's work. "As a young scientist back in the 1990s, I worked with the scientists that solved the first structures of TS," he said. "Now, decades later, we're moving forward with the first neutron diffraction data for TS to do more experiments as we decipher how this vitamin (PLP) works. The number of possible things we could do from here is limitless—it's pretty exciting."

From Science Fairs to Space

Student Experiments Help Launch New Era of Space-Based Research

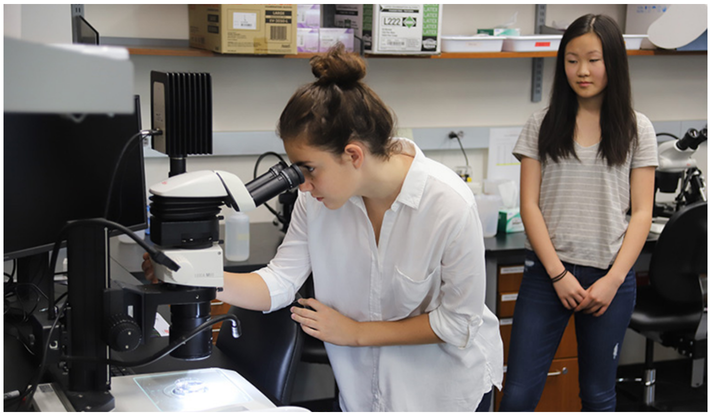
BY AMY THOMPSON, *Staff Writer*

Originally published June 22, 2022

To advance scientific discovery in new ways, scientists are taking their experiments and labs to an environment unlike any other: the International Space Station (ISS). But it is not just scientists from companies and research institutes conducting space-based studies. Students are also doing transformative research on the ISS and making significant scientific contributions, even publishing their results in peer-reviewed journals.

Through Genes in Space™, an annual student research competition founded by Boeing and miniPCR bio and supported by the ISS National Laboratory® and New England Biolabs, students in grades 7 through 12 can propose pioneering DNA experiments that utilize the unique environment of the ISS. The winning proposals are developed into flight projects carried out on the space station. Investigations from high school students participating in the Genes in Space program have resulted in six journal publications, including three in the last year.

One recent study, published in *PLOS One*, edited DNA in space for the first time as part of a project to mitigate the effects of radiation exposure during spaceflight. Another investigation, published in *Gravitational and Space Research*, developed a technique to monitor and evaluate the immune system of astronauts in space. And a third experiment, also published in *Gravitational and Space Research*, proposed a way to monitor DNA changes in astronauts as they are happening. Results from these student-led investigations have important applications in space and back on the ground.



Genes in Space competition winners Liza Reizis and Sophia Chen work on their projects in the lab ahead of launching their experiments to the ISS.

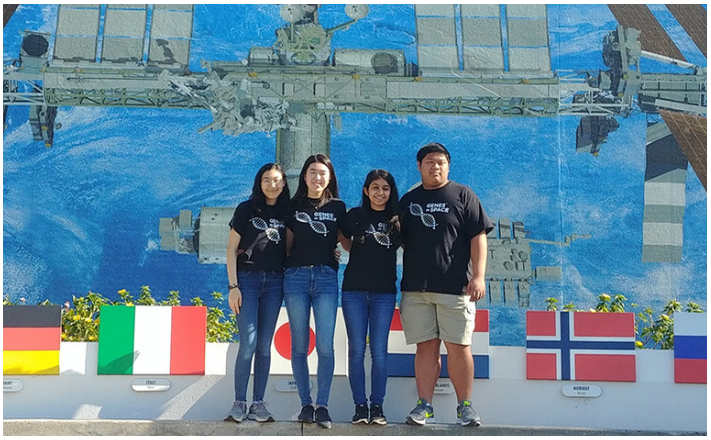
Genes in Space

"Currently, there are just so many unknowns about how life responds to the conditions of space, and we'll need to solve those mysteries before we can establish a long-term presence in low Earth orbit," said Genes in Space program lead Katy Martin. "The idea behind the competition is to open the door and invite students to lead the investigations that get us those answers."

These three recent Genes in Space experiments used a process called polymerase chain reaction (PCR) that makes millions of copies of targeted pieces of DNA, making them easier to detect and analyze. In labs on the ground, the average PCR machine, or thermocycler, is the size of a microwave. However, on the ISS, crew members perform PCR using a compact and energy-efficient instrument developed by miniPCR bio that is small enough to hold in the palm of your hand.

The first experiment to do PCR in space and validate the miniPCR machine was designed by the inaugural Genes in Space student winner, Anna-Sophia Boguraev.

"Anna-Sophia's experiment in 2016 marked the first time a molecular biology experiment was performed in space, opening up a new era of science," said Sarah Wallace, a microbiologist at NASA's Johnson Space Center. "If we can do these types of molecular biology processes using miniaturized equipment in space, then we can do them in hospitals, doctor's offices, and other resource-limited environments."



The Genes in Space CRISPR team: Aarthi Vijayakumar, Michelle Sung, Rebecca Li, and David Li. These four students designed the project that used CRISPR technology to edit DNA in space for the first time.

Genes in Space

CRISPR in Space

Four Minnesota high school students can tout something no other student or scientist can: Their experiment was the first to edit DNA in space. The investigation used a genome editing tool called CRISPR-Cas9 to create breaks in specific areas of DNA. On Earth, this technology has been used since 2012 to edit the genes of plants, animals, and human cells with great precision. It is so important to research and so widely used that two researchers were awarded the 2020 Nobel Prize in Chemistry for contributing to its discovery. Validation of CRISPR technology onboard the ISS opened the door to a whole new realm of molecular biology research.

For the 2018 Genes in Space competition, high school students Aarthi Vijayakumar, Michelle Sung, Rebecca Li, and David Li designed their investigation to help mitigate the adverse effects of radiation exposure during spaceflight. Increased exposure to radiation in space has been shown to damage DNA, leading to serious health risks, including cancer.

Cutting DNA with CRISPR-Cas9

Specific proteins in bacteria called Cas proteins—in this case, Cas9—act like molecular scissors, cutting the DNA. To control where the DNA is cut, scientists add a specific RNA strand to the Cas9 protein and insert it into a cell. Using RNA as its guide, the protein travels along the DNA strands until it finds the corresponding sequence and makes a cut.

On Earth, the human body can repair DNA damaged by breaks in the DNA strand in two ways: by adding and deleting DNA bases or by re-joining the two pieces without altering them. However, conditions in space could affect this process, so the student team proposed their experiment to see whether DNA could be successfully broken and then repaired during spaceflight.

"We looked at existing research, and people had tried to study how DNA repair is affected by microgravity by looking at the expression of different genes that are relevant to DNA repair," Vijayakumar said, "but no one had actually edited DNA in space before."

Conducted with the help of NASA astronaut Christina Koch, the student-led experiment successfully used CRISPR to generate breaks in the DNA of a common yeast and then direct the method of repair. The repaired DNA was then sequenced to determine whether its original order was restored—a process never before attempted in microgravity.

NASA astronaut Christina Koch sets up the the Genes in Space experiment that validated CRISPR technology on the ISS.

NASA

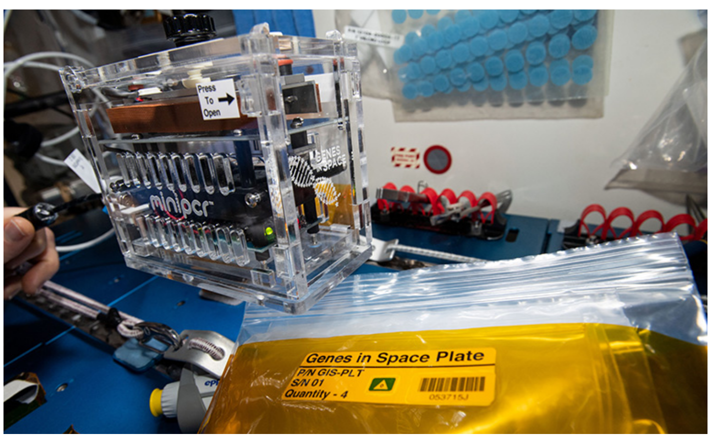
While the project was a proof of concept, the results lay the foundation for further research on DNA repair in space. Wallace said that more work is needed to fully understand the repair processes but having a miniaturized molecular biology toolkit is valuable both for space-based research and for use in hospitals and labs on the ground.

"Instead of sending samples to labs, we can take the labs to the samples," Wallace said. "We are looking at how to put these methods into other settings such as hospital rooms and resource-limited environments."

The goal is improving patient care, she added. "In today's world, human diagnostics are crucial—whether it's COVID testing or cancer screening—and it's all molecular, so the types of experiments these students are proposing are transformative."

TREC-ing Through Space

In 2017, Liza Reizis was a high school student in New York researching a homework assignment. She was fascinated by immunology but never imagined she would conduct a science experiment onboard the ISS to test a technique for monitoring the immune systems of astronauts in space.



The miniPCR machine on the ISS used to amplify DNA for Genes in Space experiments.

NASA

"During my research, I discovered that when astronauts come back from space, their immune systems are very depressed," Reizis said. "I wanted to understand what part of their immune system was affected."

This curiosity led her to do more research and design an experiment for the Genes in Space competition. Reizis learned about T-cell Receptor Excision Circles, or TRECs, which are tiny segments of DNA the body produces as a byproduct of immune cell development. These bits of DNA may seem insignificant, but she soon learned that by studying them, you can determine how many new T-cells the body is making, which directly correlates to how well a person's immune system is functioning.

For her Genes in Space investigation, Reizis focused on T-cells because they're the most prominent type of immune cell, leading the body's fight against disease and regulating the response of other immune cells. Her proposal involved using an assay to measure the amount of TRECs produced by T-cells.

Reizis postulated that this type of immune test, typically performed on infants on Earth to test for immune system disorders, could be performed on blood samples from ISS crew members. This would allow astronauts to evaluate how well their immune systems function in space. However, the process first had to be validated onboard the space station to ensure it worked as well in microgravity as it does on Earth.

Reizis designed her experiment to utilize miniPCR technology to measure the number of TRECs in biological samples sent to the space station. She sent blood samples from mice of different ages and genders to see how effective the miniPCR device was at detecting TRECs.

What is PCR?

PCR (polymerase chain reaction) is a common chemical reaction used to amplify DNA. First developed in 1983, the process essentially makes copies of specific sections of DNA targeted by small pieces of complementary DNA called primers. A cycle involving three steps is repeated about 30 times to produce billions of copies of DNA sections for analysis.

The proof-of-concept experiment was successful and paved the way for researchers to develop a safe and reliable way to monitor immune system function in space. Reizis' project also has implications for patients here on Earth, especially those affected by HIV and AIDS. This type of test could help patients more effectively measure the production of T-cells, which are directly affected by these diseases. A test using miniaturized equipment could lead to new ways of monitoring immune system function at home, improving patient care and quality of life, said Wallace.

Scanning DNA for Microsatellites

Reizis was not the sole winner of the 2017 Genes in Space competition. Washington state high school student Sophia Chen joined her in the competition's first-ever tie. Chen was interested in developing new ways to protect astronauts from the harmful effects of cosmic rays, which can damage DNA and lead to mutations that can potentially cause serious health problems, such as cancer.

Genes in Space competition winners Elizabeth Reizis and Sophia Chen with retired JAXA astronaut Soichi Noguchi, NASA astronaut Kate Rubins, ESA astronaut Samantha Cristoforetti, and Mark Mulqueen of Boeing after receiving their award at the ISS Research and Development Conference.

CASIS

"I was interested in focusing on something cancer-related—and, in particular, why astronauts have an increased risk of cancer—when I came up with the idea for this project," Chen said. "That's when I came across DNA markers known as microsatellites."

Exposure to damaging radiation and other hazards of the space environment can affect the integrity of the genome, including how the human body repairs itself. This is where DNA sequences known as microsatellites—or highly repeatable segments of noncoding DNA composed of repeating base pairs—come into play. These bits of DNA are useful as markers of genomic stability and can indicate an individual's predisposition to cancer. Changes in the length of a person's microsatellites over time suggest that they have experienced DNA damage and may be at risk of developing cancer.

Chen proposed a way to monitor changes in DNA by using miniPCR technology to amplify DNA regions with microsatellites in them. The ability to measure microsatellite sequences in space could be used to monitor astronauts' health by keeping tabs on the integrity of their DNA throughout a mission. That way, medical staff can assess whether certain individuals have an increased risk for cancer during spaceflight.

"We used both normal cell lines and cell lines known to have unstable microsatellites—which means the repeating segments are either longer or shorter than normal—in order to validate our method to see if we're able to accurately detect the microsatellites," Chen said. "With the help of miniPCR, we were able to measure changes in microsatellites in our samples."

Terrestrially, microsatellites are used for various forms of DNA profiling or genetic fingerprinting, which is useful in forensics and testing tissues for transplant patients. These segments of DNA are also used in cancer diagnosis. Results from Chen's experiment could help lead to new portable diagnostic tools that work in tandem with the miniPCR machine to help people monitor changes in their health. This would be especially beneficial to those in remote areas and developing countries who may not have access to sophisticated laboratory equipment.

Igniting a Spark in Students

"The goal of Genes in Space is to inspire the next generation of engineers and scientists," said Scott Copeland, director of ISS research integration at Boeing and co-founder of the Genes in Space program. "This is the perfect platform to do so, as the program is designed to spark imagination and foster critical thinking as well as collaboration among students by incorporating active learning and real-world experience."

Genes in Space encourages students to start thinking like researchers, enabling them to tackle real-world issues. By providing opportunities to conduct investigations leveraging the ISS National Lab, the program allows students to make real contributions to the scientific community.

Before 2016 and the debut of the Genes in Space program, the ISS lacked a molecular biology platform, said Wallace. "These student-designed experiments are truly advancing the science we're able to perform on the space station and enabling areas of research never done in space," she said. "It really blows me away at how elegant and sophisticated the students' studies have been."

Extreme Electronics

LEO as the Ultimate Technology Proving Ground

BY ANNE WAINSCOTT-SARGENT, *Contributing Author*

Originally published July 7, 2021

Computing advances continue to push the envelope for ever-smaller, ruggedized electronics that must thrive in extreme conditions, whether inside jet engines, nuclear reactors, geothermal wells deep in the Earth, or in one of the harshest environments: space.

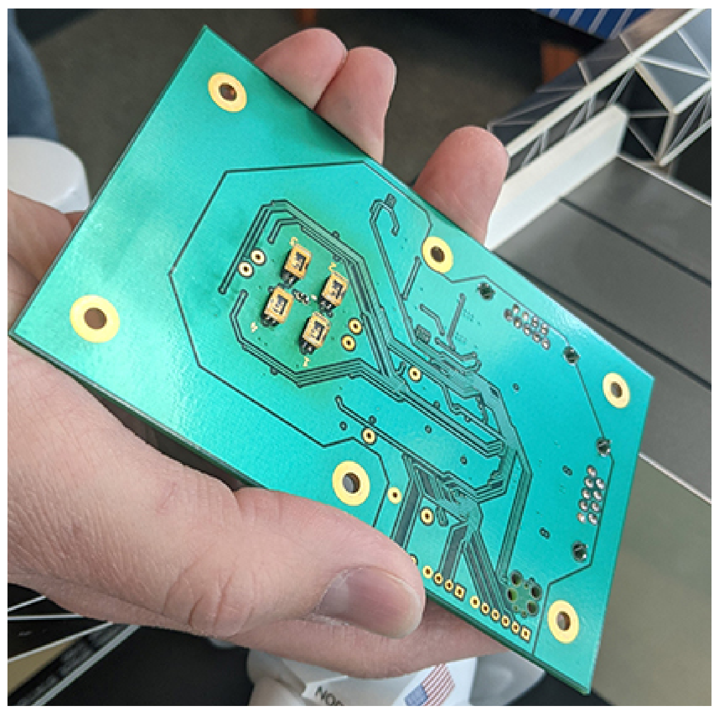
Ozark Integrated Circuits, Inc. (Ozark IC)—an Arkansas-based company that makes semiconductors work in places where normal electronics do not—developed a powerful, temperature-resistant silicon carbide ultraviolet (UV) detector purpose-built for operation in hostile environments. The high responsivity of the detector, integrated as a smart sensing system called UV eXtreme Node (UV XNode™), eliminates the need for signal amplification, which is standard in current UV detectors, thus significantly reducing the cost of the technology.

The UV XNode™ could serve as a cost-efficient UV detector system for a wide variety of remote sensing applications with valuable Earth benefits, such as improved detection of ocean-based oil spills and early fire detection in remote areas. However, the UV XNode™ first needed to be validated in the harsh space environment—which includes exposure to extreme temperature cycling, unfiltered UV radiation, ionizing radiation, and atomic oxygen (highly reactive single-oxygen atoms).

The seven-member team that developed the UV XNode™ holding the UV detector and a model of the ISS in front of them.

Ozark IC

To do this, Ozark IC sent the UV XNode™ to the International Space Station (ISS) for performance testing in low Earth orbit (LEO). For the investigation, sponsored by the ISS National Laboratory®, three UV XNodes™ spent a year on the MISSE Flight Facility, a permanent in-orbit platform from Alpha Space Test and Research Alliance that is mounted externally on the space station.



Close-up of the UVXNode™.

Ozark IC

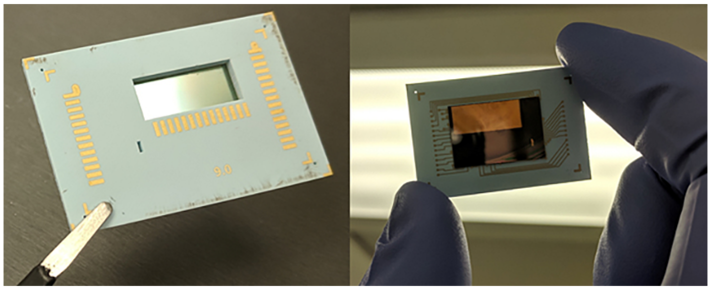
According to Jim Holmes, chief technology officer of Ozark IC, the investigation was a success. The UV XNode™ performed exactly in space as it did on Earth, with only a slight burn noted on the detector from the extreme UV conditions. During the experiment, Ozark IC received so much in-orbit data that the team had to develop a new way to capture and analyze performance measurements, with the resulting data visualization software now a core assessment tool for the company. Additionally, data from the experiment was beneficial not only to Ozark IC but also to NASA scientists conducting their MISSE experiments.

"Testing on MISSE allowed us first to determine whether our detector works in the space environment," Holmes said, "and second, advance the detector's technology readiness level so we can begin commercializing the technology."

Advancing the Technology

Known as the "rugged circuit specialists," Ozark IC started working with silicon carbide "primarily because its semiconductor properties are very good for building high-temperature electronics and UV detectors," Holmes said.

Although silicon (Si) is the most widely used crystalline semiconductor material for integrated circuits, it does not perform well for UV detection. High-energy UV photons damage Si crystals, affecting device reliability. However, this is not the case with silicon carbide (SiC), which has a higher energy threshold than Si alone and can better withstand damage from photons. This higher threshold also allows low-energy visible and infrared (VIS-IR) photons to pass through SiC without interacting, which is why SiC detectors are considered "VIS-IR blind" and SiC integrated circuits are transparent to white light.



Ozark IC's UV XNode™ contains a silicon carbide discrete sensor array (pictured here) that converts UV light into digital signals and is VIS-IR blind.

Ozark IC

Prior to Ozark IC's ISS National Lab investigation, the UV XNode™ was at a NASA technology readiness level (TRL) of 6, meaning the detector had been validated on the ground but needed testing and validation in space to advance to TRL-9 and be considered "flight-proven."

The MISSE Flight Facility on the ISS was an ideal platform to test the UV XNode™, said Holmes, because it enabled Ozark IC to do prolonged testing of the detector across the entire solar UV spectrum. While several government and commercial labs support VIS-IR radiation testing and characterization, very few terrestrial labs support testing in the solar UV spectrum, including UV-A, UV-B, UV-C, and vacuum UV.

"Reproducing the solar UV spectrum in the laboratory is difficult, dangerous, and expensive, especially for long-term endurance testing of UV detectors," Holmes said. "The MISSE Flight Facility provided Ozark IC with unique, year-long access to the solar UV spectrum without atmospheric attenuation or variation."

Leveraging the MISSE Flight Facility

Since 2001, MISSE has been used to test more than 4,000 materials, from lubricants and paints to fabrics and container seals. After securing the right to commercialize MISSE in 2015, Alpha Space upgraded its capabilities, and now the MISSE Flight Facility is increasingly being used to test complex technologies, systems, and components to assess performance in the extreme space environment, said Mark Shumbera, vice president of space services at Houston-based Alpha Space, which owns and operates the MISSE Flight Facility on the ISS.

More on MISSE

Prior to the MISSE Flight Facility, which launched to the ISS in 2018, NASA flew eight MISSE missions to the space station. The MISSE Flight Facility is a permanent commercial ISS platform that houses experiments in carriers that are launched and returned about every six months with each MISSE mission. Read more about the MISSE Flight Facility in the Upward feature "Tough Enough for Space: Accelerating Materials Testing With a New Permanent Platform."

For Ozark IC's investigation, Alpha Space integrated the UV XNode™ modules into three MISSE carriers, running functional tests to ensure everything worked before turning them over to NASA to put on the launch vehicle. The MISSE-10 mission, which included Ozark IC's modules, launched to the ISS on Northrop Grumman's 10th Commercial Resupply Services (CRS) mission in late 2018.

Once the carriers containing Ozark IC's modules arrived at the ISS, the robotic arm installed them on the MISSE Flight Facility in three orientations: ram (the forward direction of the ISS), wake (opposite to ram) and zenith (away from Earth). Each orientation offers different solar UV exposures and intensity profiles. MISSE provides time-stamped data, so the telemetry shows detection of the UV sunrise (ram), then the high-noon peak (zenith), and the finale of a UV sunset (wake).

SpaceX's upgraded Dragon spacecraft splashed down off the coast of Florida on January 13, 2021, completing SpaceX's 21st Commercial Resupply Services mission to the ISS.

SpaceX

"Ram also gets a lot of atomic oxygen, whereas wake gets very little," Shumbera said, "and zenith gets the solar noon and faces deep space where you get minimized light." These exposures provided Ozark IC with additional insight into the reliability of the UV XNode™ in the space environment.

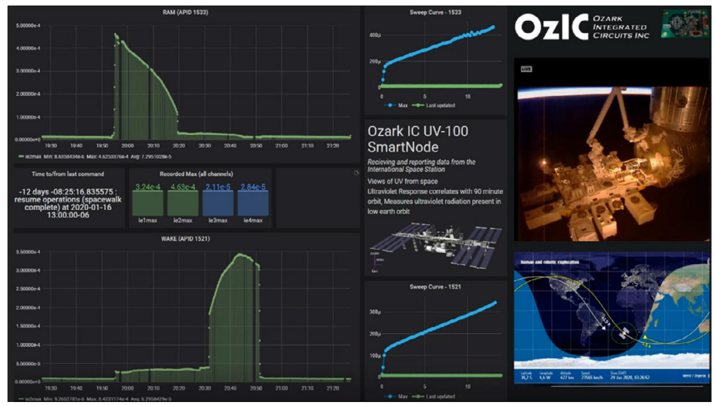
The wake- and zenith-facing MISSE carriers with Ozark IC's modules returned to Earth on SpaceX CRS-20 in the spring of 2020. And in January 2021, the last module in the ram-facing carrier came back on SpaceX CRS-21. This module benefited from an extended stay in LEO because materials flying in the same MISSE carrier required additional time in orbit.

Managing the Data Overload

Ozark IC investigators sought testing in space through the ISS National Lab to generate new data in a challenging environment, but they did not count on the data overload that their detectors experienced almost immediately. The three UV XNode™ modules, each processing four UV detector channels, yielded 12 channels that collected one data set every second. Additional data streams for the voltage-sun input vector were also captured as the station orbited the Earth and changed its angle to the sun. The sensor's location at the time of data acquisition was acquired using NASA's open API, allowing the team to correlate altitude, velocity, and position with the UV data.

Thousands of detector data points, bundled into data packets, were transmitted from MISSE, via the ISS, to the ground and then sent to Ozark IC from NASA in near real-time. All in all, Ozark IC received 2.7 million data packets throughout the investigation. Alpha Space supported Ozark IC in the initial data management process, making sure the company was receiving data around the clock, but a data overload soon became apparent. "We were drowning in data," said Holmes, noting that the company quickly realized a spreadsheet would not keep up with the constant updates.

With help from Alpha Space, NASA, and other partners, Ozark IC developed a real-time dashboard called OzIC.Lab, based in part on the open observability platform Grafana. This data visualization tool converted data into real-time performance information that was then correlated to ISS status (such as velocity, altitude, latitude, longitude, and solar heating). The dashboard included multiple views: a live feed from ISS on the upper right, UV response measurements from the UV XNode™ modules on the left, the voltage and current from the UV XNode™ modules in the middle, and location data at the bottom right showing if the ISS was in daylight or darkness.



The Ozark IC UV detector dashboard displaying real-time data from ram, zenith, wake orientations on the ISS.

Ozark IC, NASA

By design, information was constantly updating—allowing data analysts to "decode on the fly with each query of the database," and making it easy to drill down and view a lot of detailed information, said Holmes. Data received from the ISS along with the UV response from the detectors gave Ozark IC investigators a comprehensive picture. The team was able to correlate the detector measurements with ISS status and confirm the data were correct.

"Ozark IC has now implemented the dashboard as a crucial company-wide tool," said Case Kirk, Ozark IC software engineer and one of seven core team members who developed the detector system. The dashboard remotely monitors and controls experiments and serves as a data visualization tool not only for internal use but also for customers to monitor Ozark IC's products in action.

Providing Far-Reaching Value

Ozark IC was not the only one to find value in the in-orbit performance testing of the UV XNode™. The timestamps of the MISSE data enabled Ozark IC to merge ISS latitude, longitude, and altitude with every measurement, and putting this information into a searchable database has garnered the interest of NASA scientists.

Kim de Groh, senior materials research engineer in NASA Glenn Research Center's Environmental Effects and Coatings Branch, hopes to use Ozark IC's detector readings to determine UV radiation exposure for the 43 samples she and her research collaborators flew on the MISSE-10 mission.

The MISSE Flight Facility is a permanent in-orbit platform from Alpha Space Test and Research Alliance that is mounted externally on the space station.

NASA

"When I fly MISSE experiments, I need to know the solar exposure to make meaningful experiment conclusions," said de Groh.

Active UV sensors that generate real-time solar exposure data from the same location as the exposed materials and devices enable the conversion of the data to equivalent sun hours (ESH). Such sensors are ideal, explained de Groh, as they provide exposure information that can be difficult to model—such as shadowing effects on the surface of the MISSE Flight Facility from ISS components like the solar arrays. On MISSE-10, she tested materials for space structures, new shielding material for spacesuits and spacecraft, and fiber composites for use in spacecraft structural components such as antennas and space telescope parts.

"Without ESH data, my flight results cannot be correlated with spacecraft materials durability," de Groh said. "We need to know exactly how much solar UV radiation our MISSE samples were exposed to so we can correlate damage to UV exposure. This provides information needed for designing durable spacecraft."

Furthermore, according to Shumbera, the UV XNode™ detector "appears to have performed extremely well, and Alpha Space certainly will evaluate Ozark IC's sensor for possible use on MISSE."

Applications in Space and on Earth

After withstanding a year of continuous exposure to the solar UV spectrum without degrading, the UV XNode™ is now space-proven and poised for use in numerous space-based applications. Holmes credits the company's ISS National Lab investigation with enabling the UV XNode™ to achieve a TRL of 9, the final and highest level of readiness signaling that the technology is ready for commercialization.

Ozark IC plans to further miniaturize its UV detector technology and fly a pixelated detector array, potentially for UV imaging and UV spectrometer remote sensing applications. In the future, the UV XNode™ may also have applications in space exploration missions, such as rovers on the surface of Venus.

Back on Earth, jet and diesel engine makers may also see value in Ozark IC's SiC technology. UV light is a by-product of combustion processes such as charge-compression ignition in diesel engines, fuel efficiency jet engines, and gas-powered generation systems. The XNode™ could have valuable applications in monitoring engine health and real-time fuel analysis.

The ISS serves as a powerful test bed in LEO, and the time on Alpha Space's MISSE Flight Facility allowed Ozark IC to prove its UV XNode™ worked in space while advancing the detector's TRL. "This really was a good result," Holmes said. "It validated the robustness of the UV XNode™ and our ability to fly this technology again in the future."

On the Edge of the Edge

Taking Supercomputing to Space

BY AMELIA WILLIAMSON SMITH, *Upward Managing Editor*

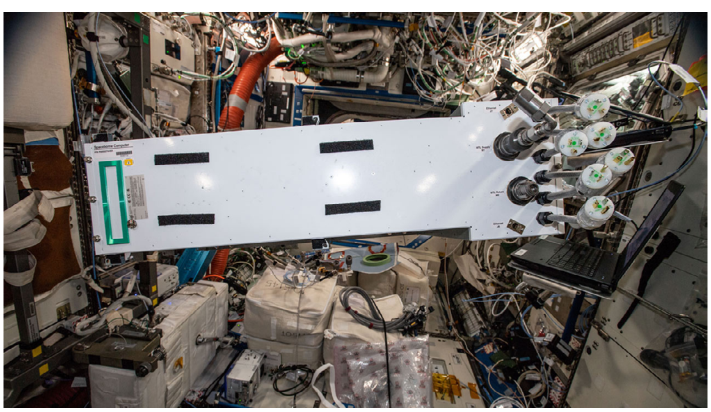
Originally published May 7, 2021

On Earth, scientists are used to having high-performance computers at their fingertips. Such computing capabilities are critical to analyze the rich data from experiments and extract the insights needed to make valuable scientific and technological advancements. But what if your laboratory is not on Earth—but in space?

Can you take a high-performance computer with you that has not been "hardened" to withstand spaceflight? Can it survive the rough forces of launch? Will it work in the extreme space environment, where solar flares, galactic radiation, and cosmic rays may interfere with computing?

Researchers at Hewlett Packard Enterprise (HPE) wanted to find out, so they packaged an unmodified commercial off-the-shelf (COTS) high-performance computer and sent it to the International Space Station (ISS). HPE's computer, Spaceborne Computer-1 (SBC-1), remained on the ISS for more than 1.5 years (657 days) in the first long-term demonstration of supercomputing capabilities from a COTS computer system on the space station. The SBC-1 mission was sponsored by the ISS National Laboratory®.

"The vision for the Spaceborne Computer program is: Can astronauts fly with the latest COTS computer, and will the hardware stand up to the harsh conditions if it is given some smart software to take care of itself? And SBC-1 was a great success," said Eng Lim Goh, HPE senior vice president and chief technology officer for artificial intelligence (and principal investigator of the SBC-1 mission).



Hewlett Packard Enterprise's Spaceborne Computer-1 onboard the ISS.

NASA

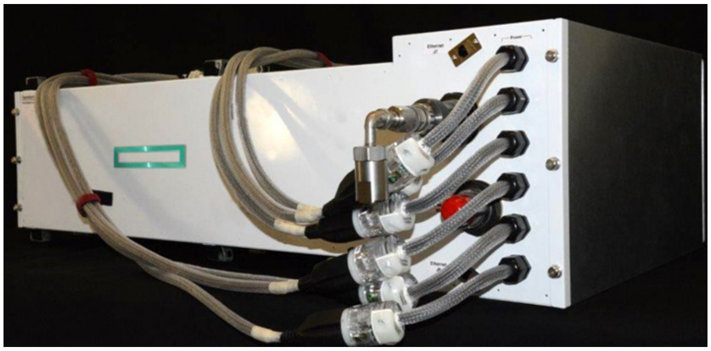
Not only did SBC-1 work in space—the demonstration was nearly flawless. With an innovative approach to protect the system's hardware using specially designed software, SBC-1 was able to continue successful operations throughout the duration of the mission, despite the extreme conditions in low Earth orbit, and never once got an incorrect answer or had an interrupt due to the computer. SBC-1 also achieved a significant milestone while in orbit: running one teraflop, which amounts to more than one trillion calculations per second, for the first time in space.

The Spaceborne Computer-1 mission patch.

Hewlett Packard Enterprise

Space-Based Supercomputing Success

The project was so successful that HPE sent a follow-on mission to the space station through the ISS National Lab, Spaceborne Computer-2 (SBC-2), which launched on Northrup Grumman's 15th Commercial Resupply Services (CRS) mission and was just installed and began operations onboard the ISS. SBC-2 will incorporate lessons learned from SBC-1 but will also feature twice the processing power and will include graphics processing units and other artificial intelligence and edge processing capabilities. More importantly, it will also allow real users to leverage the system for in-space processing.



Spaceborne Computer-1

Hewlett Packard Enterprise

Sending high-definition imagery and large datasets from the ISS to Earth for processing is time-consuming and uses a lot of network bandwidth. Processing the raw data on the ISS and then sending down the results would save both time and bandwidth.

"This system will be valuable going forward," Goh said. "And if it proves itself even further, I think there is strong motivation to provide it to astronauts for long-duration space exploration, where the communication time back to Earth gets longer and you can rely less and less on immediate responses from computing power on Earth."

HPE's successful demonstration benefits not only space-based computer systems but also computers on Earth that operate in harsh environments, said HPE's Mark Fernandez, lead software engineer for SBC-1 and principal investigator for SBC-2.

"Part of HPE's mission is edge computing, and we have a whole line of products that are meant to be on the edge—which could be on an offshore oil rig, in the depths of a mine, or in the very back of a massive warehouse," Fernandez said. "Processing data on the edge is valuable to HPE, as is learning what works and doesn't work and how to take those consequential actions when things go awry, and there's no better place to do that than at the edge of the edge, which is the space station."

A Consequential Design: Hardening With Software

To be able to continuously operate in the extreme space environment, HPE's computer system needed to be autonomous. It had to not only monitor the hardware but also take action when needed to avoid failures and loss of data, Fernandez said.

Traditional "hardened" electronics are expensive and are designed around the anticipation of specific conditions that could damage a computer, such as radiation. However, in space, it is not always easy to know the exact conditions a computer may encounter. So HPE took a different approach—instead of designing the system for what might damage the equipment, the team considered the possible consequences of the damage and what mitigation would be necessary to continue successful operations.

"We built a whole suite of software around that idea, which we collectively call 'hardening with software,' and it proved to be invaluable during SBC-1," Fernandez said. "The software would kick in and slow the computer down as needed."

The software monitored all aspects of the hardware, and when the system detected conditions outside the established parameters, it would alert the HPE team on the ground and go into a safe state until the problematic conditions passed. Although the system could not determine what was causing the problem, the software was designed to reduce performance in a stairstep fashion to keep the hardware safe.

The HPE SBC-1 team received the 2018 ISS Innovation Award in Technology Development and Demonstration for the team's innovative work on SBC-1. Mark Fernandez (third from the left) and John Kichury (second from the right) of HPE accept the the award on behalf of the SBC-1 team.

CASIS

As a first step, the system would drop down from optimal performance and reduce its speed to run more slowly. If the problematic conditions persisted, the system would then drop down to idle. Finally, if needed, the system would power itself down to remain safe.

"Looking at all the parameters, the system would go through this stairstep decline in performance," Fernandez said. "You would rather be running slowly than not running at all, you would rather be powered on than powered down, but you would rather be powered down than damaged."

Establishing Proof of Concept

After arriving at the ISS, SBC-1 was installed and achieved its first milestone: powering up. “Installation was very exciting,” said HPE’s David Petersen, lead hardware engineer for SBC-1 and SBC-2. “It was a very iterative process, and when we energized the system and got a ping command back, that alone was a big accomplishment.”

The HPE SBC-1 team was awarded NASA’s Exceptional Technology Achievement Medal for the first successful demonstration of a COTS supercomputing platform on the ISS and for executing more than one trillion calculations per second for a year. (The HPE SBC-1 team, from left to right: Mike Scott, Rob Behringer, Mark Fernandez, Dave Petersen, Eng Lim Goh, John Kichury)

Hewlett Packard Enterprise

The HPE team sent two identical computer systems to the ISS for the SBC-1 mission and kept two identical systems on Earth as controls. This allowed the team to confirm SBC-1 was getting the correct results and to compare the time it took to get the results on Earth versus in space.

After installation, the team began running several benchmark codes to assess SBC-1’s performance and establish proof of concept. While running the High-Performance Linpack benchmark, which is used to rank supercomputers according to speed, SBC-1 achieved another major milestone: running an impressive 1.1 trillion calculations per second.

High-Performance Linpack Benchmark

The High-Performance Linpack benchmark measures a computer system’s floating-point computing power. It measures how quickly the system can solve a set of linear equations to estimate the speed at which the system can perform.

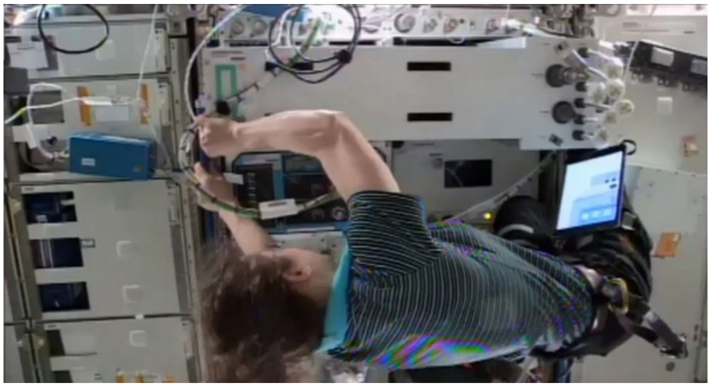
“I think it must have been the first time astronauts in space were able to get that much computing power—one trillion floating point operations per second,” Goh said. “And SBC-1 ran it quite quickly. The system completed the benchmark before the space station completed one revolution around the Earth.”

Overcoming Challenges in Orbit

SBC-1 continued successful operations throughout the mission despite the challenging conditions in space. A common issue encountered was network loss of signal back to Earth, lasting from a few seconds to half an hour. In addition to loss of signal, power interruptions also presented challenges. The ISS is powered by solar cells, and the power distribution on station can fluctuate. There were also several instances of unplanned power loss—from a circuit breaker tripping to an astronaut accidentally bumping into SBC-1 and powering it off.

“We planned for the consequence of losing power; we didn’t really plan for an astronaut’s knee to bump into SBC-1’s emergency power switch,” Fernandez said lightheartedly. “The power was cut off, and when the power was restored and it was safe to begin operations again, we picked up right where we left off with no loss of data, so that was pretty exciting.”

SBC-1 did experience more correctable errors than the Earth-based control systems. The HPE team thinks this is likely due to solar flares, galactic radiation, and other phenomena encountered in space. During the SBC-1 mission, the team ran one of the two systems on the ISS as fast as possible and the other as slow as possible to see if one would encounter more errors than the other.



NASA astronaut Christine Koch prepares SBC-1 for its flight home.

NASA

Running more slowly uses less power and less cooling, and it takes longer to get the answers, but the team thought it would also make the system less susceptible to errors. However, that turned out to be false. Both the fast- and slow-running systems encountered about the same number of correctable errors, Fernandez said. This is important because it showed that running at a high speed does not appear to increase the likelihood of errors.

The space environment also took a particular toll on SBC-1's solid-state disks—out of 20 solid-state disks, 9 failed during the mission. The system had redundant copies of all data, so no data was lost, but the team plans to try different methods to better protect the solid-state disks during the SBC-2 mission.

Ending a Successful Mission and Beginning In-Space Processing

After more than 1.5 years of successful operations, SBC-1 was powered down for its return to Earth on SpaceX CRS-17. "Decommissioning was probably the hardest day in the whole process," Petersen said. "Because of the success of the system for so long, the day we actually had to power it down was really a tough day."

SBC-1 returned to Earth on SpaceX's 17th Commercial Resupply Services mission, which splashed down in the Pacific Ocean on June 3, 2019.

SpaceX

After the SpaceX capsule splashed down in the Pacific Ocean, the HPE team was anxious to retrieve SBC-1 and do the "shake, rattle, and roll" check to see how the system fared during its return. "When I applied power to the system, it booted right back up, and in a matter of minutes, we were back running the same benchmarks we were running in space," Peterson said. "To successfully go through launch and then return and have the hardware come back and power up without any deformation or degradation I think was exceptional."

The SBC-1 mission was originally planned to last one year but was extended due to changes in the ISS cargo schedule. During its extended time on station, SBC-1 had its first real user. NASA Langley's Entry Descent and Landing team used SBC-1 to run code to advance the software being developed for the Mars lander. The code ran with no errors and even ran faster on SBC-1 than on the team's earthbound computers. For the SBC-2 mission, HPE's computer system will be open to any investigator that could benefit from in-space processing. "We will run a set of benchmarks to prove that it works as we did in SBC-1 and then open it up for use out there on the edge of edge," Fernandez said.

HPE Spaceborne Computer-2

Hewlett Packard Enterprise

In-space processing could significantly benefit both scientists running experiments on the space station and ISS crew members. For example, a scientist studying lightning from the ISS may only need imagery taken so many seconds before and after a lightning strike. Instead of sending all the imagery to Earth to extract the data of interest, SBC-2 could process the imagery onboard the ISS and only send down the relevant data.

Additionally, objects 3D printed on the ISS must go through a quality control process in which cameras inspect the object to ensure the accuracy of the print. Instead of sending all this imagery to Earth for processing, SBC-2 could process it onboard the ISS and immediately notify the crew that the object is safe to use.

Looking to the future, in-space computing will also be critical for missions to Mars and beyond. "The purpose of exploration is insight, not the data," Fernandez said. "If we can take computational resources with us on our mission and they can give us the correct answers, then we can collect the data, process it, and hopefully come up with the necessary insights to continue on our mission." ▮

Shooting to Higher Orbit

SlingShot's Flexible Launch Model Offers Affordable, Fast Path to LEO

BY ANNE WAINSCOTT-SARGENT, *Contributing Author*

Originally published December 1, 2020

The future low Earth orbit (LEO) economy depends on faster, more frequent rides to space. SEOPS, LLC is addressing this urgent need with its SlingShot system, an innovative small satellite (smallsat) deployer that hitches a ride on Northrop Grumman's Cygnus resupply spacecraft and releases smallsats into a higher Earth orbit above that of the International Space Station (ISS). As a commercial facility on commercial resupply launch vehicles servicing the ISS, SlingShot offers a flexible, affordable rideshare for smallsats and provides the longer in-orbit time needed to prove out technology critical to the successful commercialization of LEO.

SEOPS, an ISS National Laboratory® Commercial Service Provider based in Houston, has completed four SlingShot missions since the facility's first deployment in February 2019. SlingShot provides opportunities for smallsat deployments in a cost-effective manner that aligns with the current resupply flight schedule. The higher-orbit trip comes after Cygnus completes its primary commercial resupply services mission to the ISS. SEOPS designed and built SlingShot from scratch and secured its own customers for use of the facility—completing NASA's safety review process in only three months and fully deploying in less than a year, said SEOPS CEO Chad Brinkley.

"Our approach serves as a blueprint for the commercialization model embraced by NASA," said Brinkley, "where the private sector will lead space launch and operational advances into LEO, and NASA can be one of many customers."

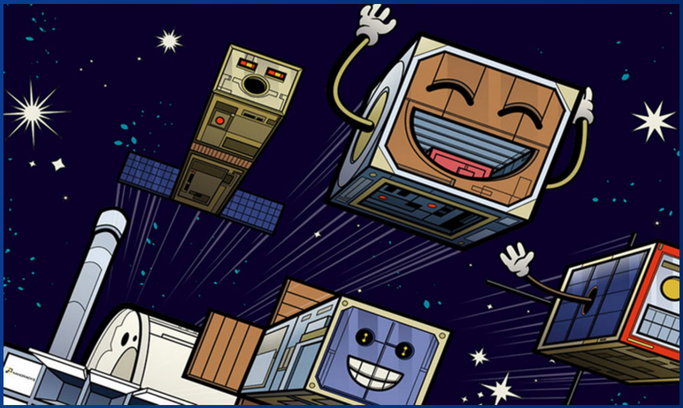
SlingShot has expanded LEO access to a broad array of users—from NASA to commercial firms and universities—allowing them to raise the readiness level of their technology at greatly reduced cost and risk. By de-risking technology development and demonstration, SlingShot is helping to democratize LEO and to accelerate the development of a robust and sustainable LEO market economy.

NASA

Leveraging the ISS for Smallsat Deployment

Commercial partners are helping to establish the ISS as a reliable launchpad for smallsats with a wide variety of missions aimed at benefiting life on Earth. CubeSats are cheaper and lighter than larger satellites, making them easier and less risky to launch into orbit. Smallsat deployment from the ISS provides affordable access and helps lower the barriers to entry to space—facilitating increased commercial innovation, enabling new scientific discoveries, and driving a robust economy in LEO.

Read more in the Upward feature "Jumpstarting the CubeSat Revolution With Reliable Launch from the ISS."



Building a Strong Partnership

SEOPS partners with Northrop Grumman on SlingShot missions—for its first SlingShot mission, Cygnus initially delivered more than 7,400 pounds of science and supplies to the ISS. To date, SlingShot has deployed 14 CubeSats and supported four hosted payloads. Northrop Grumman's Cygnus first began flying missions above the ISS in November 2016 to facilitate NASA science objectives, including CubeSat deployments. Early extended Cygnus missions included the Saffire Fire Experiment led by researchers at NASA Glenn Research Center and the OA-4 mission, where Cygnus helped perform re-entry observations.

The Cygnus spacecraft as it leaves the ISS for the first SlingShot mission with Lynk's payload attached.

NASA

After Cygnus berths to the ISS, ISS crew members install the SlingShot deployers onto the front of Cygnus using a custom modular bracket, which houses the cluster of deployers. Cygnus then moves to a safe distance from the station before Northrop Grumman flight controllers in Dulles, Virginia, propel the vehicle to a higher altitude where they deploy the payloads. Cygnus then re-enters Earth's atmosphere and burns up harmlessly over the Pacific Ocean.

Dave Hastman, vice president of exploration and operations for Northrop Grumman, operator of the Cygnus spacecraft, says carrying secondary payloads on Cygnus requires working within a compressed schedule. "The combined Cygnus and SEOPS team has learned significant lessons to facilitate continued successful operation of the SlingShot deployer and hosted payloads," Hastman said.

Currently, eight out of ten SlingShot users are government clients, including NASA, the Department of Defense, and the U.S. Air Force. The Air Force and Texas-based Hypergiant Industries, an artificial intelligence satellite tech company, plan to use SlingShot to test the Air Force's Chameleon Constellation of LEO-based reconfigurable satellites. The Air Force designed this new breed of military satellites to re-task and respond in minutes to space threats, from new orbital debris to a conventional weapon or a cyberattack.

Flexible Launch Options

Over the past decade, there has been a significant rise in the number of smallsats being launched into orbit. CubeSats, small cube-shaped satellites measuring 10 cm on each side and weighing less than 1.4 kg (or about three pounds), accounted for 42% of all smallsats and 33% of all satellites launched into orbit last year. The number of CubeSats launched increased seven-fold from 2012 to 2019, according to analytics and engineering firm Bryce Space and Technology. The ISS has played a key role in enabling this rapid increase—more than 300 CubeSats had been launched from the space station as of January 2020, and SlingShot is helping to expand access even further.

In addition to deploying CubeSats, SlingShot can also host fixed payloads that remain attached to Cygnus while it is in orbit. These fixed payloads use Cygnus as a satellite bus for power, attitude (position in space) control, and communications for longer missions.

While the ISS operates 350 kilometers from the ground, SlingShot reaches 450 to 480 kilometers above the Earth via Cygnus's post-ISS-berth orbit. This higher orbital path provides "a sweet spot for mission duration and Earth coverage" that allows you to see 90% of the Earth, Brinkley said, noting that the higher a payload launches into orbit, the longer it can remain in microgravity to conduct tests and prove out its technology.

NASA astronaut Jessica Meir poses in front of the closed hatch of the Cygnus space freighter from Northrop Grumman. Attached to the hatch is the SlingShot smallsat deployer loaded with eight CubeSats that were deployed into Earth orbit for communications and atmospheric research several hours after Cygnus departed the orbiting lab on Jan. 31, 2019.

NASA

A SlingShot Success Story

One successful SlingShot user is Lynk, a startup that has completed four successful technology demonstrations using SlingShot deployment—including sending the world's first text message from an orbiting satellite to a standard mobile phone on Earth in February 2020. Lynk has raised $10 million since its first technology demonstration with SlingShot.

Lynk is building a smallsat constellation to enable anywhere-anytime communications across the world using standard phones, with the goal of providing affordable cellular coverage everywhere on Earth. By connecting more people around the world, the company is helping to overcome the digital divide, which disproportionately affects developing nations and communities with low socioeconomic status. Connected communities can innovate faster and participate in the digital economy, which drives economic growth.

By leveraging SlingShot and the facility's frequent rides on resupply missions, Lynk has been able to achieve rapid prototyping and development. Lynk's first three SlingShot payloads were fixed payloads on Cygnus, and the company's fourth payload used a free-flying microsatellite.

"We have our fourth prototype up, and all have used SlingShot," said Lynk co-founder and CEO Charles Miller, a 30-year serial space entrepreneur. "Our ultimate goal is delivering global broadband directly to your phone, everywhere. We want to bring connectivity to the 90% of Earth's surface that is outside the bounds of terrestrial wireless."

Using SlingShot, Lynk was able to deploy its technology faster while being capital efficient.

"We were able to focus our money on the payload," Miller said. "What's critical to us in a commercially competitive market is how do you innovate fast? Part of that answer has been leveraging the ISS and SlingShot."

Lynk launches a payload an average of once every six months, Miller said, and he considers SlingShot one of the most cost-effective options for smallsat launches. Building on Lynk's successful demonstrations using SlingShot, the company is now developing its own free-flyer mission.

Student-Built CubeSats Leverage SlingShot

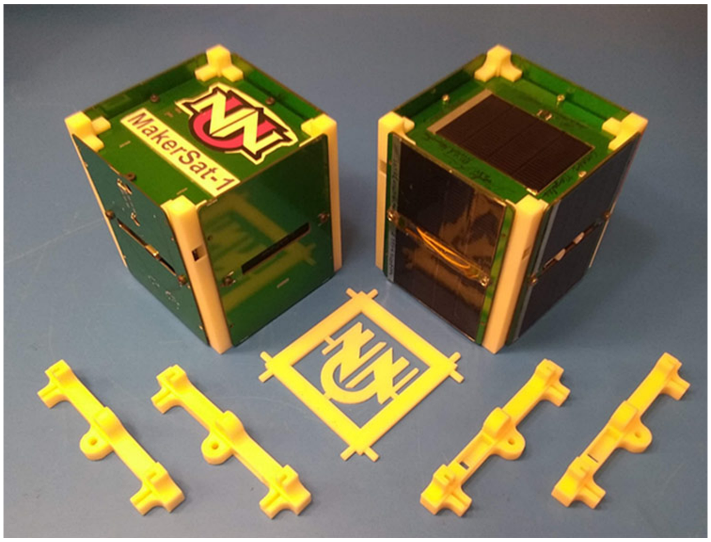
Academia is also benefiting from SlingShot's flexible deployer. Last year, two CubeSats built by students from Northwest Nazarene University (NNU) in Nampa, Idaho, were launched into space using SlingShot.

The MakerSat team (L to R: Mitch Kamstra, Ben Campbell, Braden Grim, Connor Nogales, Josh Griffin, Stephen Parke)

Northwest Nazarene University

The students' first CubeSat mission on SlingShot, Radio Frequency Tag Satellite (RFTSat), was developed in partnership with the Georgia Institute of Technology and deployed in August 2019. RFTSat tested a new 5.8 GHz radiofrequency tag sensor system using backscattering communication. This system will allow data collection from an array of small sensor tags located at the extremities of very large orbiting structures of the future. These postage-stamp-sized tags require no battery or wires—they are powered and read from a centralized reader using radiofrequency energy (the transfer of energy by radio waves).

"RFTSat can sense anything on a large space structure, from radiation to temperature to fields to vibrations—whatever sensors you want to put out there," explains Stephen Parke, professor of electrical engineering and chair of physics and engineering at NNU. "The tags can last indefinitely because they don't have any batteries."



MakerSat-1 CubeSat flight and engineering hardware, including the white polymer structural parts 3D printed on the ISS.

Northwest Nazarene University

The students' second CubeSat to use SlingShot, MakerSat-1, was deployed in February 2020 and utilized structural parts that were 3D printed onboard the ISS using Made In Space's Additive Manufacturing Facility (AMF). Both MakerSat-1 and its precursor mission, MakerSat-0 from NNU, studied four polymers that can be used for 3D printing structures in space to see which would best endure the destructive orbital environment, where UV, plasma, and ionizing radiation are commonplace.

Parke says data from both MakerSat missions found that 3D printed polyactic acid (PLA) was best for short-term missions of one to three years, while Ultem® (polyetherimide/polycarbonate), a UV-resistant plastic material, would work best in longer-term missions.

Both SlingShot-deployed NNU CubeSats will likely remain in orbit for two or three years and have not experienced any orbital degradation so far, said Parke. He envisions space-based missions one day being devised on the fly onboard the ISS, using stowed satellite components that are snap-assembled with polymer AMF-printed structures and deployed into orbit from the ISS.

Into the Future

Looking ahead, SEOPS CEO Brinkley remains excited about the prospect of continuing to fly the SlingShot system, which provides a cost-effective, reliable way to get into upper orbit. Northrop Grumman reiterated its commitment for future SlingShot missions. "The Cygnus program envisions continuing to support SEOPS with the deployment of CubeSats and expanding on the successful hosted payload operations performed thus far," Hastman said.

Brinkley says SlingShot's success has opened up new opportunities for SEOPS to expand its core capabilities beyond launch systems to be a true systems integrator for missions beyond LEO.

"SlingShot has given us a lot of mission-critical past performance that translates to market credibility," Brinkley said. "We know how to integrate our deployment systems successfully on any rocket with our team, not just the launch systems we build, and we have proven we can fly safely, leveraging the ISS infrastructure. I can't think of a better model for commercialization of LEO."

It's Getting Crowded Up There

Towing Away Trash in Space

BY ANNE WAINSCOTT-SARGENT, *Contributing Author*

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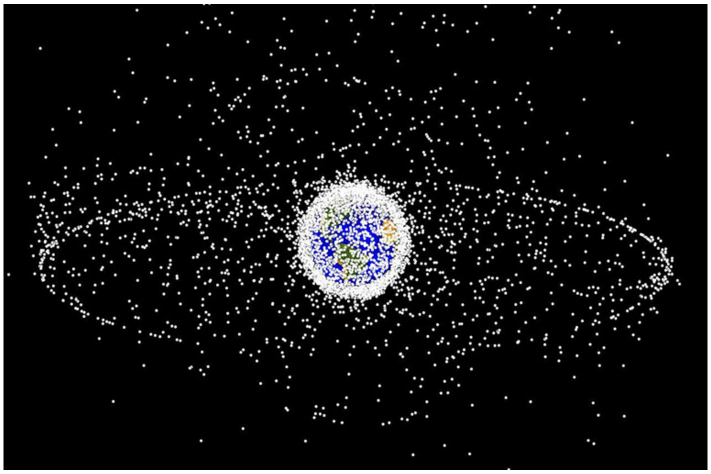
No one likes trash—not in landfills and not in space. Yet the mounting problem of orbital debris continues to increase as space gets more congested, making orbital operations more hazardous and more costly. To address this growing problem, several companies are evaluating technologies for the capture and removal of space debris—and one Houston-based company, Airbus DS Space Systems, recently completed such testing through the International Space Station (ISS) National Laboratory.

Two investigations that Airbus conducted on the ISS National Lab in recent years provide new insight on how to stabilize and tow spinning space debris, whether the object carries fuel or solid mass. Research such as this is critically important as the problem of space debris continues to grow, posing a threat to working spacecraft and satellites in orbit. It is vital to address this increasing concern as the economic development of low Earth orbit expands and as we as a species venture farther into space to achieve the lofty goals of returning to the Moon with Artemis and embarking on the next journey beyond.

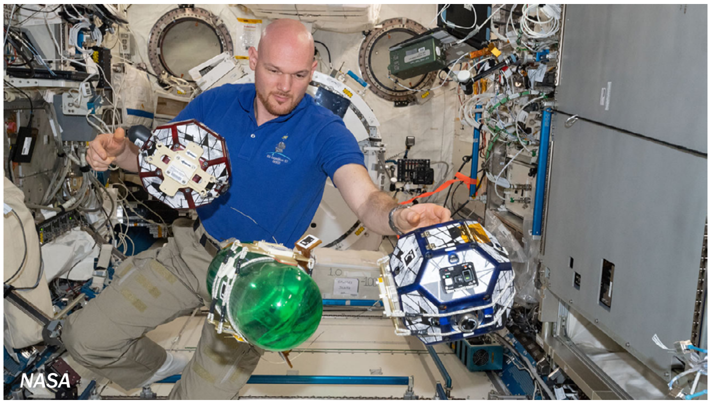
An Expanding Problem

Since the first artificial satellite, Russia's Sputnik, first rocketed into orbit in 1957, some 8,900 satellites have followed suit, providing valuable tracking, Earth observation, and communications capabilities to the world. But that number is about to grow significantly with the wave of new high-throughput mega constellations of satellites heading into low Earth orbit.



This is a computer-generated image of objects in Earth orbit that are currently being tracked. Approximately 95% of the objects in this illustration are orbital debris, i.e., not functional satellites. The dots represent the current location of each item.

NASA



NASA

"We can count more than 100,000 satellites that are projected to launch in the next decade," said Ted Muelhaupt, principal director and manager of the Corporate Center for Orbital and Reentry Debris Studies (CORDS) at The Aerospace Corporation, a federally funded research and development center focused on national security space.

"If we continue with business as usual, as we did for the first 50 years of the space age, then we're going to create an untenable mess."

Space debris puts working satellites at risk for collisions, exposing space companies and government agencies to losses easily in the hundreds of millions of dollars. From the perspective of another object in orbit, space debris might move many times faster than a bullet. Because of its relative velocity, space debris the size of a blueberry could create the impact of a falling anvil.

Today, the Space Surveillance Network (SSN), operated by the U.S. Space Force Command, tracks objects in space. Radar and optical sensors observe and track objects larger than a softball in low Earth orbit and objects basketball sized or larger in higher, geosynchronous orbits. Sensors determine which orbit the objects are in, and that information is used to predict close approaches, reentries, and the probability of a collision. Other nations also run space object tracking systems.

The U.S. Space Force Command estimates there may be more than half a million objects with a diameter larger than one centimeter orbiting the Earth and currently tracks more than 26,000 objects with a diameter of 10 centimeters or larger. Such space debris makes space operations hazardous and is becoming an increasing problem as additional companies and countries join the space economy.

In 1978, NASA scientist Donald J. Kessler predicted space overcrowding in low Earth orbit could lead to collisions between objects, which would trigger a cascade of more debris causing other collisions. Currently, geostationary satellites and those in low Earth orbit must carry extra fuel to perform maneuvers to enter a safe graveyard orbit at the end of their operational lifetime to avoid collisions with other satellites. If other means to avoid space debris became available, companies could use this fuel to extend their satellites' operational lifetime.

You Capture Debris, Then What?

Several companies are tackling the problem of space debris by studying debris capture methods ranging from the use of harpoons to deploying giant nets or robotic arms. But once an object is captured, then what? The process of de-orbiting larger debris from space principally occurs in four phases: capture, stabilize, tow, and deorbit.

Hans-Jürgen Zachrau, senior project manager with Airbus Space Systems, led two ISS National Lab- investigations to explore the dynamics of stabilizing and towing larger space junk such as an uncontrolled satellite. "As objects are moving in space, there is velocity and trajectory," Zachrau said. "After capturing an object, you need to stabilize it; you need to enter into a controlled movement. That's what we did."

These tests followed an earlier "NetCapture" experiment, in which a net deployed outside the ISS captured a spinning shoebox-sized object. Launched a safe distance from the ISS in open space, the NetCapture experiment had only one shot within a matter of seconds and no way to repeat it, Zachrau said.

However, performing more difficult maneuvers—to stabilize and tow an object in space—requires multiple attempts and positioning, making a test in open space impractical. The ISS served as the perfect test bed for research on such maneuvers, given that these types of experiments require several minutes and many repetitions to correct and optimize the maneuvers.

The first SPHERES Tether Demo experiment being performed by European Space Agency astronaut Thomas Pesquet.

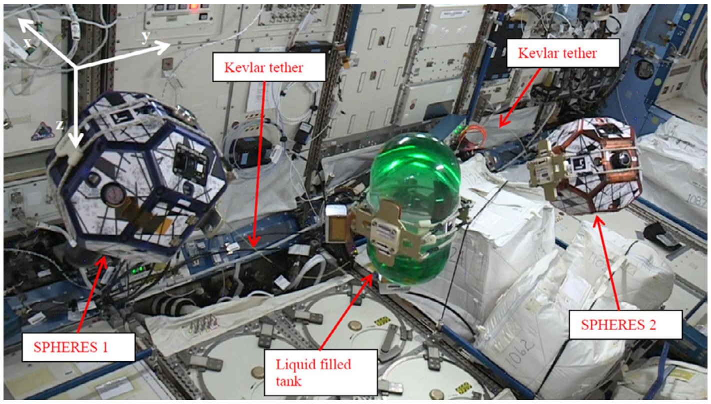
NASA

Airbus conducted its first ISS National Lab investigation in 2016, the "SPHERES Tether Demo" experiment, to assess the dynamics of satellites being tugged from different angles. In 2018, Airbus conducted a second investigation on the ISS National Lab, the "SPHERES Tether Slosh" experiment, to evaluate ways to actively steer a passive body that contains liquid in space, such as satellites holding fuel reserves.

Both investigations used Synchronized Position Hold, Engage, Reorient, Experimental Satellites (SPHERES), free-flying satellites that maneuver using small puffs of compressed gas. The experiments were done in collaboration with NASA's Ames Research Center, the managers of the SPHERES system, and the Massachusetts Institute of Technology, the developers of the SPHERES system. For the SPHERES Tether Slosh experiment, NASA's Kennedy Space Center loaned Airbus a sloshing tank, having previously performed related studies on liquid sloshing in space.

The Dynamics of Tugging Debris

The SPHERES Tether Demo investigation included a series of tests to explore the flight dynamics as one tug satellite pulled a target satellite under different starting and control conditions. The ISS crew also tested the tension and torque of two different tethers—a nylon monofilament and a Kevlar thread—in 31 maneuvers. Airbus augmented its findings from these tests with data from accelerometers, gyroscopes, and positioning sensors on each SPHERES satellite.



The SPHERES Tether Slosh setup on the ISS.

NASA

Airbus performed all the baseline and most of the optionally defined tests using both tether materials—the Kevlar (a more rigid material) and nylon monofilament (more elastic). Although the SPHERES operational envelope only allowed for a 40-cm tether length, the Kevlar tether was preferred for follow-on experiments because it provided better predictability of its properties. With the results obtained from the SHPERES Tether Demo experiment, Airbus adapted its dedicated software tools to analyze the stability and dynamics of flexibly coupled systems. Furthermore, the data were used to validate a simulation environment for tethered Active Debris Removal (ADR) missions.

Building on this first experiment, Airbus conducted the SPHERES Tether Slosh investigation, which was done in four separate sessions on the ISS from January to September 2018. The goal was to evaluate methods to actively steer a passive body that contains liquid—such as a disabled spacecraft with fuel in its tank—in space, when it is unknown whether the remaining fuel is liquid or frozen. The tests included both a liquid and a solid mass tank with otherwise similar mass properties. The ISS crew ran test profiles with both tanks to allow comparison of the same maneuvers.

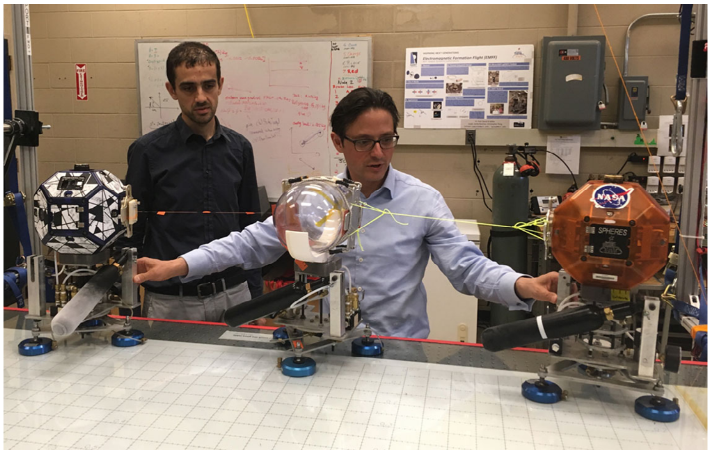
The Airbus team was unsure how easy it would be to safely steer an object containing liquid in space. The liquid could slosh around in unpredictable ways, potentially making space maneuvers difficult. However, the results surprised them.

"The liquid mass tank was pretty tame and easier to steer, while the solid mass tank had a much more aggressive dynamic—the force was so powerful that it could actually affect the direction of the satellite," Zachrau said. "The crew had to secure the equipment because, otherwise, the tank would crash into the SPHERES."

Philipp Behruzi first envisioned the sloshing experiment as the senior expert in the Fluid Mechanics group at Airbus Defence and Space before becoming part of ArianeGroup GmbH, an Airbus and Safran joint venture. According to Behruzi, this type of experiment had never been done, and what they found was not what they were expecting. "We discovered that a liquid-filled object behaves much easier when we tow it away than a rigid body," Behruzi said. "That's because some of the energy goes into the sloshing of the liquid, and in that context, the liquid behaves like a dampener."

Behruzi went on to explain, "In space, if you want to brake, you can't—and that's where you get into problems. Without the dampening effect, all the energy is kept as kinetic energy—there is no braking of the system."

Another key finding was that the rope must be attached through the center of gravity of both the towing object and of the object being towed, because otherwise, the momentum produced causes the path of the towing object to deviate.



Danilo Roascio of MIT and Philipp Behruzi at MIT Labs conducting a first experimental setup of SPHERES Tether Slosh.

MIT

"By aligning both the towing and the controlling SPHERES vehicles through the center of gravity of the object being towed, we obtained good control over the dynamic movements of the overall system throughout the variety of our experimental profiles," Behruzi said.

Toward a Cleaner Future in Low Earth Orbit

Researchers hope that the Airbus experiments will fuel further research in the area of space debris cleanup. “It will take a concerted effort,” Zachrau said. “No one can do it alone, so we must work as a worldwide community to address the space debris problem.”

Muelhaupt added, “A clean space environment is in everyone’s self-interest,” noting that the Airbus experiments are advancing the technology readiness needed to safely remove existing space debris. Before the world has a viable cleanup mechanism, Muelhaupt contends that space firms and innovators like Airbus will have to go through several generations of testing technologies.

Spurring Investment in Space Debris Cleanup

While the broader societal needs and growing risks around space debris have been broadly acknowledged, a path to incentive mechanisms that would support significant private-industry investment in addressing the problem of space debris is much less clear. Encouragingly, in September 2019, the European Space Agency commissioned its first mission to remove debris from orbit, ClearSpace-1, which is currently targeted to launch in 2025.

In addition, the Japanese government plans to promote investment in technologies to clean up space debris, and earlier this year the Japan Aerospace Exploration Agency (JAXA) awarded the initial phase of its first debris removal project to Astroscale Holdings. In December 2019, the U.S. government provided an update of its Orbital Debris Mitigation Standard Practices, but several industry stakeholders have expressed that the update does not go far enough to address the current space debris situation.

As the world gets serious about active debris removal missions, the ISS will play a significant role. Given the diverse nature of space debris and the need to more accurately track a growing debris population, there is a critical need for additional research and testing of debris removal technology, and the ISS is an ideal platform for both. Although there is still a long way to go in developing reliable scenarios to securely de-orbit objects from space, the Airbus investigations are an important initial step toward understanding the complexity of towing objects in space. ■

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