INTERNATIONAL SPACE STATION

BENEFITS for Humanity

2022

View of solar array and radiator panels over Earth limb taken by Expedition 52 crew. Credit: NASA

International Space Station

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This book was developed collaboratively by the members of the International Space Station (ISS) Program Science Forum (PSF), which includes the National Aeronautics and Space Administration (NASA), Canadian Space Agency (CSA), European Space Agency (ESA), Japan Aerospace Exploration Agency (JAXA), State Space Corporation ROSCOSMOS (ROSCOSMOS), and the Italian Space Agency (ASI).

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Letter from the Chief Scientist

On November 2, 2020, the International Space Station (ISS) entered its third decade of human-tended operation and science. The first decade of station was the decade of construction; the second decade, moving from initial research to full utilization. We are now in the decade of results.

During the past 20 years, the space station evolved from an outpost on the edge of space into a highly capable microgravity laboratory. Now results are compounding, new benefits are materializing, and the third decade is building on these last two decades of research.

This orbiting laboratory enables researchers from around the world to take advantage of microgravity, exposure to space, and a unique perspective on Earth to conduct groundbreaking experiments through an environment accessible only through the space station. Although the International Space Station is a partnership among many nations, each with distinct goals, every partner shares a unified goal: to use this amazing laboratory for the betterment of humanity. With more than 20 years of experiments now conducted on station, more breakthroughs are materializing than ever before.

Benefits for Humanity 2022 highlights the diversification of benefits stemming from microgravity research—for society, science, exploration, and the economy. This edition focuses on new areas of scientific study formed, future technologies for the exploration of the Moon and Mars, lifesaving discoveries, and companies and jobs created from these endeavors.

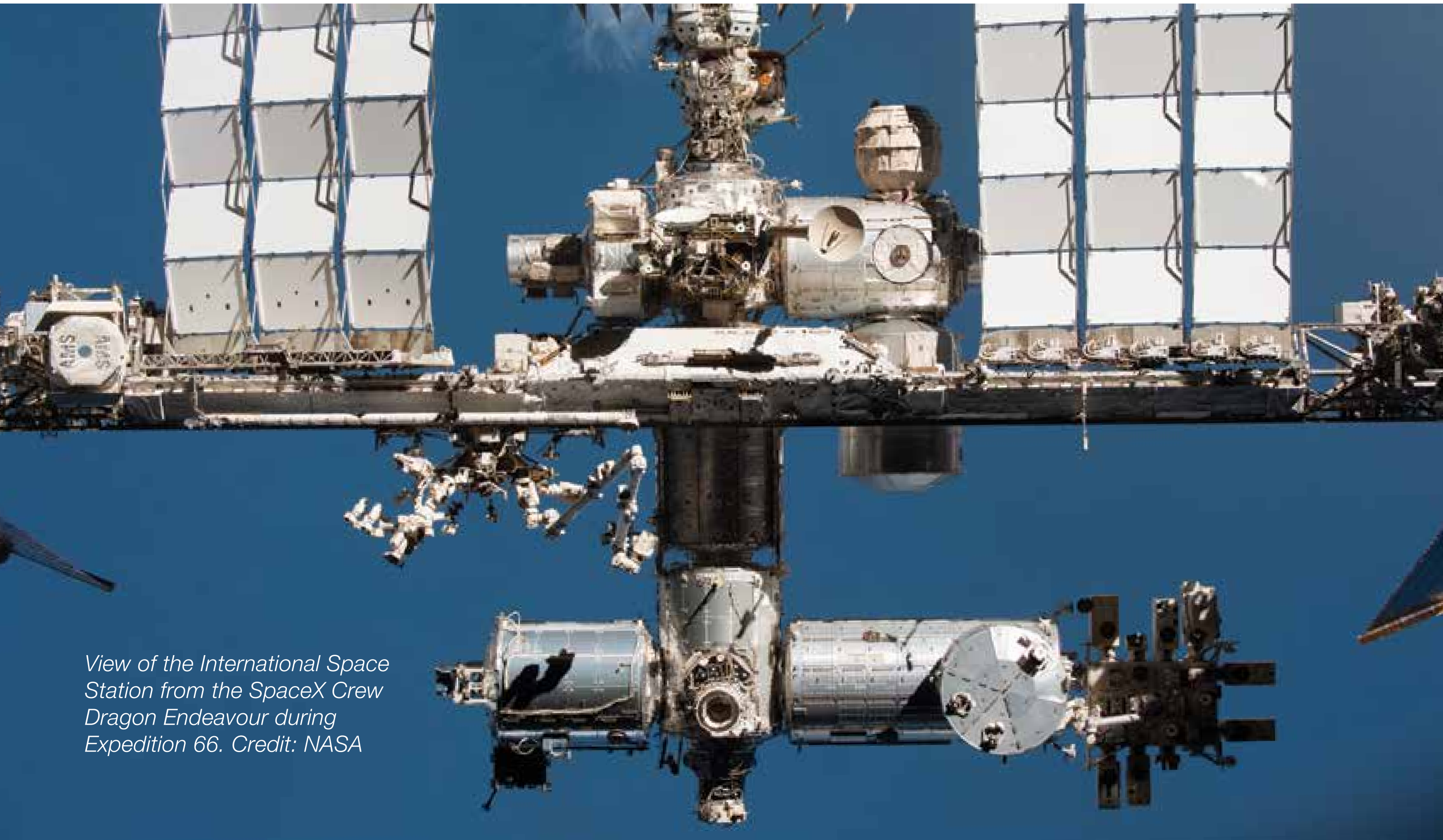
The International Space Station advances scientific understanding of our planet, improves human health, develops advanced technologies, and provides a space platform that inspires and educates the leaders of tomorrow—a legacy and influence that will be felt for decades to come.

For more information on the ISS Benefits for Humanity publication, go to: https://www.nasa.gov/stationbenefits

The ISS Benefits for Humanity 2022 is a product of the International Space Station Program Science Forum (PSF), which includes the National Aeronautics and Space Administration (NASA), Canadian Space Agency (CSA), European Space Agency (ESA), Japan Aerospace Exploration Agency (JAXA), State Space Corporation ROSCOSMOS (ROSCOSMOS), and the Italian Space Agency (ASI).

Dr. Kirt Costello

International Space Station Chief Scientist



View of the International Space Station from the SpaceX Crew Dragon Endeavour during Expedition 66. Credit: NASA

Your Orbiting Laboratory

An Introduction to the International Space Station

View of the International Space Station from the SpaceX Crew Dragon Endeavour taken on November 8, 2021. Credit: NASA

> *I always thought being an astronaut would be an amazing thing. I never thought it would be a real possibility. But the thing that always inspired me about it was this idea that we get to explore and do it in a way that benefits all of humanity.*
>
> *-NASA astronaut Mark Vande Hei*

Why Do Research on the International Space Station?

NASA astronaut and Expedition 67 Flight Engineer Jessica Watkins enjoys the view of the Earth below from inside the International Space Station's seven-windowed cupola. Credit: NASA

The International Space Station is a modern marvel. Only 400 kilometers (250 miles) above our heads, it streaks spectacularly across the sky at 28,200 kilometers (17,500 miles) per hour, orbiting the Earth every 90 minutes. The station carries an impressive array of research facilities supporting hundreds of experiments at any given time across every major science discipline. It can host up to eight visiting vehicles and accommodate 11 crew—all while providing an amazing view featuring 16 sunrises and sunsets per day.

But what is so special about an orbiting lab? What makes scientists willing to tackle the significant challenges of planning and scheduling research, designing and building hardware, and committing extraordinary time and effort to complete experiments?

It's all about location.

An orbiting laboratory provides researchers with the unique features of low-Earth orbit (LEO): long-duration microgravity, exposure to space, and a unique perspective on our planet. These attributes enable scientists to conduct innovative experiments that cannot be done anywhere else.

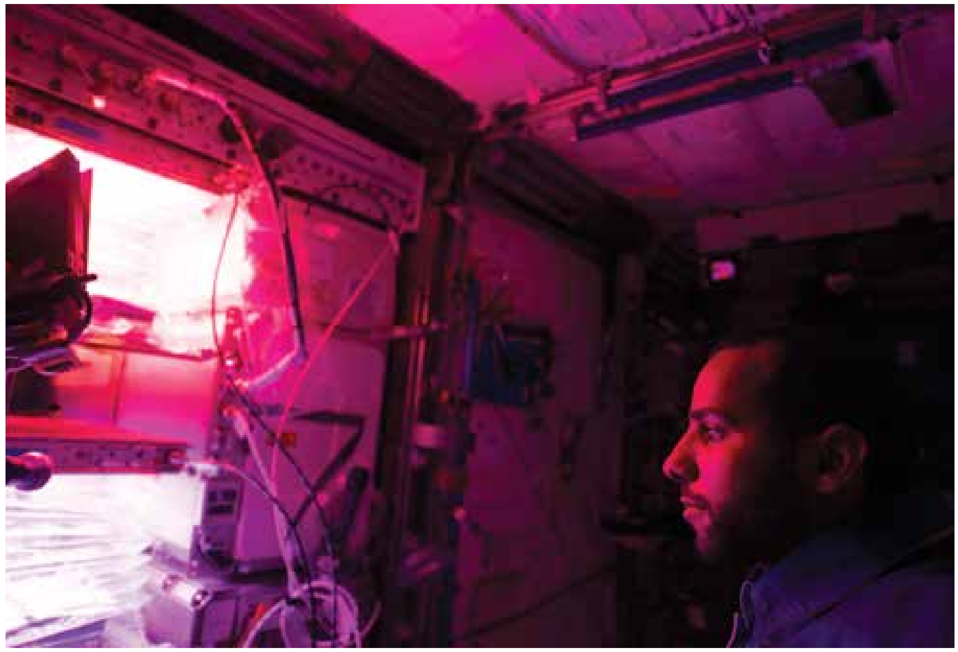
On Earth, everyone and everything experiences the constant pull of Earth's gravity. Scientists looking to eliminate that force for their experiments use freefall. An object in freefall experiences almost zero net gravitational force (thus the term microgravity) as it drops. While scientists have several ways to generate microgravity conditions on Earth, the event can only last for a short time. An orbiting laboratory is in a permanent state of microgravity as it continuously falls around the Earth in a nearly perfect circle, providing consistent, long-term access to reduced-gravity conditions.

Sustained microgravity is a game-changer for scientists across many disciplines. For example, humans are uniquely tuned to Earth's gravity. This force affects our entire body, from how hard our heart pumps to the density of our bones. Plants use gravity to determine which direction their roots should grow. Removing gravity gives biologists unique insights into the responses of all forms of life to new stresses.

Many physical and chemical processes also change when you remove gravity, opening up opportunities to study boiling, melting, fluid and gas mixing, protein crystallization, and even an ultra-cold state of matter known as Bose-Einstein Condensate in ways

These circular star trails and the rainbow of colorful lights on Earth below them were created by combining 18 images with prolonged exposures into a composite photo. This image shows the unique vantage point station provides for both astrophysical and Earth observations. Credit: NASA not possible on Earth. For example, without gravity hot air does not rise, causing flames to become spherical and behave differently. Surface tension and capillary forces dominate fluid behavior in microgravity, allowing scientists to observe and measure the subtleties of these forces drowned out by gravity on Earth.

> “Crew members can collect unscheduled data of an unfolding event such as a storm or volcanic eruption using handheld digital cameras.



Personal portrait taken of UAE Spaceflight Participant Hazzaa Ali Almansoori in the ambient light of the Veggie experiment. Credit: Hazza Ali Almansoori

The space station’s orbit differs from sun-synchronous orbits of typical remote-sensing Earth satellites, providing unique observation opportunities for scientists. A lower altitude allows instruments to obtain greater detail, and the station passes over a majority of Earth’s landmass and population centers. The combination of a low-altitude fast orbit, a high orbital angle, and the slow rotation of the Earth underneath produces unique opportunities for observing a variety of locations, atmospheric phenomena, and natural disasters from different angles and with varying lighting conditions.

Having crew on board also generates options not available with typical satellites. Crew members can collect unscheduled data of an unfolding event such as a storm or volcanic eruption using handheld digital cameras. They also can provide real-time assessment to determine whether environmental conditions, such as cloud cover, are favorable for data collection.

The orbiting laboratory’s location at the upper edge of the Earth’s atmosphere allows researchers to study the effects of exposure of materials, electronics, and even microorganisms to the harsh space environment for long periods of time, then return those items and samples to the ground for detailed analysis. In addition, the station provides power, data transmission capacity, and repair capability for astrophysics instruments collecting data largely blocked by Earth’s atmosphere or magnetic field.

Throughout this book you will find examples illustrating the wide range of scientific disciplines and technology demonstrations benefiting from International Space Station research. The impacts of these efforts can all be traced back to key aspects of the station’s unique location—the edge of space.

Hundreds of downlinks have allowed students in the tens of thousands worldwide to directly engage with station crew, inspiring the next generation of explorers. Credit: NASA

The International Space Station and a docked Soyuz vehicle as seen from an approaching space shuttle in Aug. 2001. Credit: NASA

A Foothold ON THE Edge of Space

Expedition 1 kicks off science aboard the International Space Station

On November 2, 2000, Russian cosmonauts Yuri Gidzenko and Sergei Krikalev and NASA astronaut Bill Shepherd commenced continuous operation of the world's first truly international space laboratory. At the start of Expedition 1, the International Space Station was more of an outpost on the edge of space than a microgravity laboratory. Consisting of the U.S. Unity node and Russian Zarya and Zvezda modules, the station offered less than 200 cubic meters (260 cubic yards) of pressurized volume, roughly equivalent to a one-bedroom apartment, and about 3 kilowatts of power.

During their 4-month mission, the Expedition 1 crew worked on approximately 50 science and technology investigations. Many focused on the performance of critical station systems; documentation of the acceleration, vibration, and the acoustic environments on board; and studies of their physical adaptations to extended time in the microgravity environment. These investigations helped to lay the groundwork for the future evolution of research aboard the International Space Station.

As part of crew health monitoring, the first of many investigations of crew viral shedding on station was initiated. Studies of this phenomenon, first documented on space shuttle missions, led to the identification of reactivation of latent herpes viruses in crew as a potential health risk on long-duration space missions. This reactivation is typically "subclinical," meaning crew are not truly sick and do not exhibit symptoms.

While changes in immune function during a space mission, such as viral shedding, continue to be a focus in preparation for exploration efforts to the Moon and Mars, this specific research also provided direct benefits to the rest of us on Earth. Technologies for saliva and urine testing designed for this

Expedition 1 crew members eat fresh oranges in the Zvezda Service module. Pictured, from the left, are Russian cosmonaut Yuri Gidzenko, NASA astronaut William Shepherd, and Russian cosmonaut Sergei Krikalev. Credit: NASA

research were patented and led to rapid virus-detection tests that are used today for diagnosing common ailments on Earth such as mononucleosis, herpes, and chicken pox.

The Plasma Kristall-3 (PK-3) investigation was one of the first physical science experiments performed on the space station. The Max Planck Institute for Extraterrestrial Physics in Germany and the Institute for High Energy Densities, part of the Russian Academy of Sciences, collaborated on this study of the formation and behavior of plasma crystals. Plasma crystals form under certain conditions in a complex (dusty) plasma. There, the electrically charged dust particles arrange in a regular macroscopic crystal lattice. In microgravity, scientists can grow plasma crystals larger than possible on Earth, making the station ideal for these experiments. Indeed, these collaborators have continued performing experiments over the life of the station.

Cold plasma can permeate many materials and spread evenly and quickly. It can disinfect surfaces and has been proven to neutralize some drug-resistant bacteria within seconds. Thus, there are many Earthbound benefits from research into plasma crystals. Plasma research on station from this collaboration has contributed to the licensing of seven families of patents and the creation of three companies active in industries dealing in hygiene, medicine, water purification, odor control, car exhaust technology, and medical treatments for wound care and skin disease treatment.

Products in development currently include a miniaturized wound treatment device that can create plasma from ambient air without using a gas tank. This capability could expand uses from hospital settings to doctors' offices, patients' homes, and even remote locations worldwide.

Expedition 1 also initiated crew photography-based Earth observations research on the space station. From the platform's unique vantage point, the crew used hand-held cameras to capture images of hurricanes, cities, and geographical features of interest. These photos added to long-running image-capture programs reaching back

On January 23, 2001, the crew photographed a plume of volcanic ash from Popocatépetl volcano, Mexico. Credit: NASA

to the 1960s for both the Russian and U.S. space programs.

Crew photography has continued over the life of the station. As of September 2021, nearly 4 million Earth photos are publicly available to researchers interested in studying environmental changes over many years and decades. Well over 3 million of them have been taken aboard the International Space Station over the past 20 years.

As impactful as these first research accomplishments were, Expedition 1's greatest accomplishment was to set the stage for all who followed. Over the next two decades of station use, new modules and research facilities have been added and the variety of research supported by the orbiting laboratory has expanded into new fields of science and technology while contributing to economic development.

Cosmonaut Valeri Tokarev during space station Expedition 12 with the PK-3 hardware. Credit: Max Planck Institute for Extraterrestrial Physics, Germany

See Also:

Down to Earth: Q and A with Cosmonaut Sergei Krikalev

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AzTech Sat-1 floats away from the space station. It is the first satellite designed and built by students in Mexico that was deployed from the International Space Station. Credits: NASA/Nanoracks

From Outpost to Orbiting Laboratory

The International Space Station grows up—20 years of research and human presence in low-Earth orbit

Over the more than 20 years of continuous habitation since the first crew stepped aboard, the International Space Station has evolved from an orbital outpost into a state-of-the-art scientific lab. This growth included the connection of over a dozen major components, expanding the interior pressurized volume by a factor of five (over 900 cubic meters [1,200 cubic yards]), roughly equivalent to a five-bedroom home. To support the growing research portfolio, power generation increased by more than an order of magnitude.

In 2011, the International Space Station program officially transitioned from a focus on assembly to prioritizing utilization, including research, technology development, educational engagement, and commercial development. Crew time available for scientific and technology activities increased from lows of 10-20 hours per week to highs in excess of 125 hours per week. Bandwidth for data downlinks increased, enabling faster transmission

MISSE materials exposure device being installed on the space station for the first time in August 2001. The first externally mounted experiment conducted on the space station, MISSE-1 exposed 750 material samples to space for about 18 months. Credit: NASA

of research data and allowing for more real-time monitoring of experiments. Data downlinks also enable real-time support of station crew by expert scientists on the ground as they conduct hands-on research. As a result, while it took 10 years to initiate the first 1,000 investigations on the station, the second 1,000 took half that time.

The first dedicated science lab, the U.S. Destiny module, was added in 2001. Three additional dedicated science modules have been added to the station since: the ESA (European Space Agency) Columbus and Japan Aerospace Exploration Agency (JAXA) Kibo modules both launched in 2008, and the Russian Nauka module launched in 2021.

Each dedicated science module increased the laboratory's capacity to host both internal crew-tended research and external experiments conducted on platforms attached to the outside of the station. JAXA's Kibo module added an additional airlock to the orbiting laboratory. This small airlock, with a sliding mechanism that allows crew to easily transfer science payloads from inside to outside, was specially designed to support external research and reduce the number of crew spacewalks needed for conducting science activities.

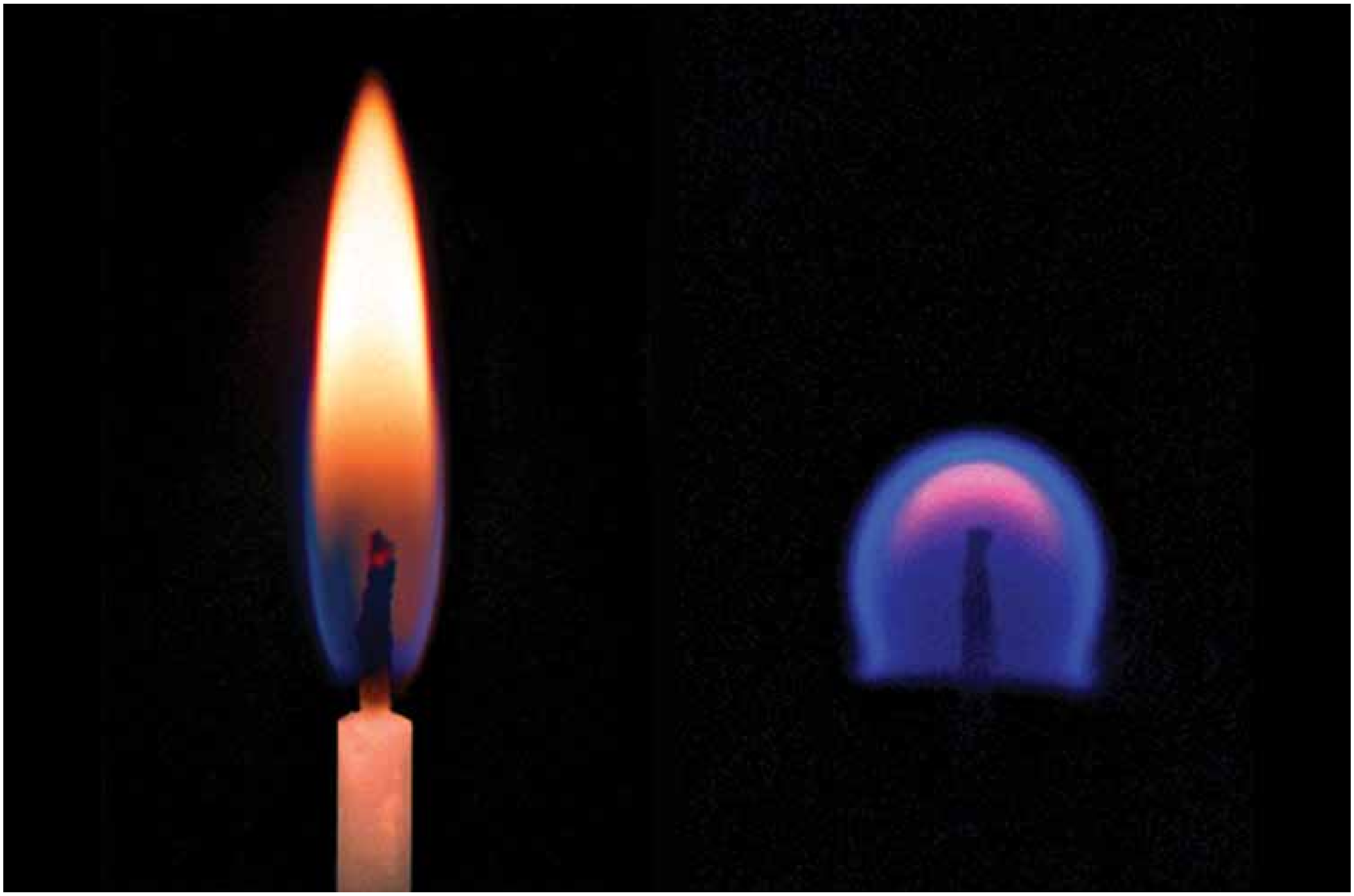
The attachment of the iconic Cupola greatly increased capability to provide crew photographs of Earth and celestial objects for use by researchers. The Cupola also provides crew visibility to support control of the space station's remote manipulator system, anchored by the Canadian Space Agency's (CSA)'s Canadarm2 and Dextre.

Canadarm2 and Dextre support spacewalks, maintenance, arriving vehicles, and external research activities. Impactful spinoff technologies have been created, thanks to the Canadarm2. Related technology has transformed the way surgery is performed with tools such as neuroArm, an image-guided, computer-assisted neurosurgery device; and the Image-Guided Autonomous Robot (IGAR), a digital surgical tool that provides increased access, precision, and dexterity for performing highly accurate, minimally invasive procedures.

External experiments on station can take advantage of exposure to the harsh environment of space surrounding the orbiting lab. The space station's first external science facility, the Materials on ISS Experiment (MISSE), entered service in 2001 and hosted eight sets of experiments over the next 15 years. Exposure experiments such as these lead to development of better materials for future spacecraft, spacesuits, and structures needed for space exploration. These materials can also improve radiation protection, solar cell performance, and concrete manufacturing on Earth.

Tests like these continue today using the upgraded MISSE Flight Facility (MISSE-FF). An example of a growing number of commercially owned and operated facilities supporting research aboard the station, MISSE-FF eliminates the need for crew to go outside the station by employing the Canadarm2 to attach exposure samples for testing.

Experiments housed on the outside of station also provide valuable opportunities for conducting Earth observation and astrophysical research. External platforms provide power, command, thermal control, and data-throughput for instruments capturing data on Earth's atmosphere,



On Earth, hot air rises, making flames long and thin. In microgravity, flames are spherical in shape. Credit: NASA

oceans, and ecosystems, or collecting astrophysical data on cosmic rays or observing at wavelengths largely masked from ground instruments by the atmosphere.

Due to its unique orbit, the space station also provides a vantage point that complements Earth observation data gathered from other satellites. It also offers researchers an opportunity to test and refine their instruments before committing them to long-duration satellite or robotic exploration missions where repair or replacement are not possible.

Although not originally designed for this purpose, station has also become a prolific deployer of small satellites. In 2005, cosmonauts kicked things off by manually releasing the State Space Corporation ROSCOSMOS (ROSCOSMOS) Nanosputnik during a spacewalk. This satellite flew for four months, successfully performing a full program of flight experiments.

The addition of JAXA's Kibo module and its airlock paved the way for many more small satellites to be deployed from station. Facilities were installed on the orbiting laboratory in 2013 by JAXA and U.S.-based company Nanoracks to automate the deployment process. As of November 2020, more than 250 CubeSats have been deployed from the space station into low-Earth orbit.

As the space station research portfolio has expanded, a significant number of investigations have focused on disease. In particular, the station has been invaluable in conducting protein crystal growth experiments.

Researchers discovered that they could produce higher quality protein crystals in microgravity than on Earth in experiments conducted on Mir and on space shuttle missions. The human body contains more than 100,000 types of proteins. Each protein provides information related to our health. Studying these proteins by crystallizing them helps us learn more about our bodies and potential disease treatments. Crystals grown aboard the station as a part of experiments sponsored by JAXA, ROSCOSMOS, NASA, and ISS National Lab have helped identify the structures of proteins relevant to understanding and treating diseases ranging from Duchenne Muscular Dystrophy to heart disease and cancer.

Plasma research, initiated by the first station crew, continued over the next two decades as well. The Plasma Kristall-4 (PK-4) study built on this work by designing an apparatus to study dusty or complex plasma. Dusty plasmas are often found in nature—in the tails of comets and planetary rings, for example. Additionally, dust particles can change many technological processes in industry, such as microchip manufacturing, etching, and vapor deposition.

Over time, capabilities for supporting biological and human health research have expanded to include facilities for studying the impact of microgravity on plants, microbes, and animals. Species as diverse as tardigrades, nematodes, fruit flies, squid, and

NASA astronaut Jessica Meir configures the Light Microscopy Module for the Advanced Colloids Experiment-Temperature-4 (ACE-T-4) study. ACE-T-4 examined the transition of an ordered crystal to a disordered glass to determine how increasing disorder affects structural and dynamic properties. Credit: NASA

rodents have all been studied on the station, and investigations that focus on the genetic, cellular, and systems levels have been supported.

More than 180 instruments and facilities have been employed to conduct space station research over its lifetime, steadily expanding the scope of research that the orbiting laboratory can support.

The addition of the Combustion Integrated Rack (CIR) in 2009 opened up unique opportunities to the combustion research community that have helped move that field of science forward. Removing the effects of gravity from combustion allows for exploration of the basic principles of flames and has even led to the discovery of a new type of combustion known as cool flames.

"Station experiments also extend to areas that directly benefit products that consumers use every day.

Likewise, the additions of ESA's Electromagnetic Levitator (EML) and JAXA's Electrostatic Levitation Furnace (ELF) in 2014 and 2015, respectively, have benefitted materials science. These facilities suspend samples in a magnetic or electric field, eliminating the possibility of contamination from sample containers as the samples are melted by powerful lasers. Supported research includes investigations into nucleation and solidification kinetics in undercooled melts and the developing microstructure, as well as measurement of highly accurate thermophysical properties of liquid metallic alloys at high temperatures.

Results of one ESA-sponsored study published in 2020 documented thermophysical property data (liquid surface tension, viscosity, mass density, and specific heat capacity) for three nickel-based superalloys widely used in turbines and other energy applications. Scientists had not been able to experimentally define these properties accurately enough on Earth. A detailed understanding of the properties of specific materials is essential for advancing manufacturing efficiency and product quality.

Station experiments also extend to areas that directly benefit products that consumers use every day. Toothpaste, 3D printing, pharmaceuticals, and shampoo all stand to benefit from improvements made thanks to years of research on colloids aboard the space station. Mixtures of tiny particles suspended in a liquid, colloids include natural mixtures such as milk as well as manufactured products from shampoo to medicine to salad dressing.

Companies such as Procter & Gamble have used station research to study how to keep a product liquid enough to dispense easily and yet prevent ingredients, or particles, from clumping together and settling. Space station research has contributed to three new patents for the company.

As humanity continues to reach farther into the solar system, the International Space Station continues to be a testing ground for technology and science that could benefit deep space missions. For example, the Italian Space Agency (ASI) and NASA collaborated on the Portable On Board Printer 3D experiment, which helped pave the way for the printing of materials on station. Hundreds of samples have been created in multiple printing facilities. Astronauts on long voyages need to be able to make their own spare parts, tools, and materials essentially on demand—both for routine needs and to adapt quickly to the unforeseen. In-space manufacturing using 3D printing could be an answer.

Having a crewed space station in orbit for more than 20 years has allowed for the collection of crucial data on how the human body responds to living in space for extended periods. For example, Space-Associated Neuro-Ocular Syndrome (SANS) was identified in many station astronauts. Symptoms include swelling in the optic disc, which is where the optic nerve enters the retina, and flattening of the eye shape, causing changes in vision. Station serves as a platform for testing ways to prevent or reverse these changes and preserve astronaut vision throughout future missions and when they return to Earth.

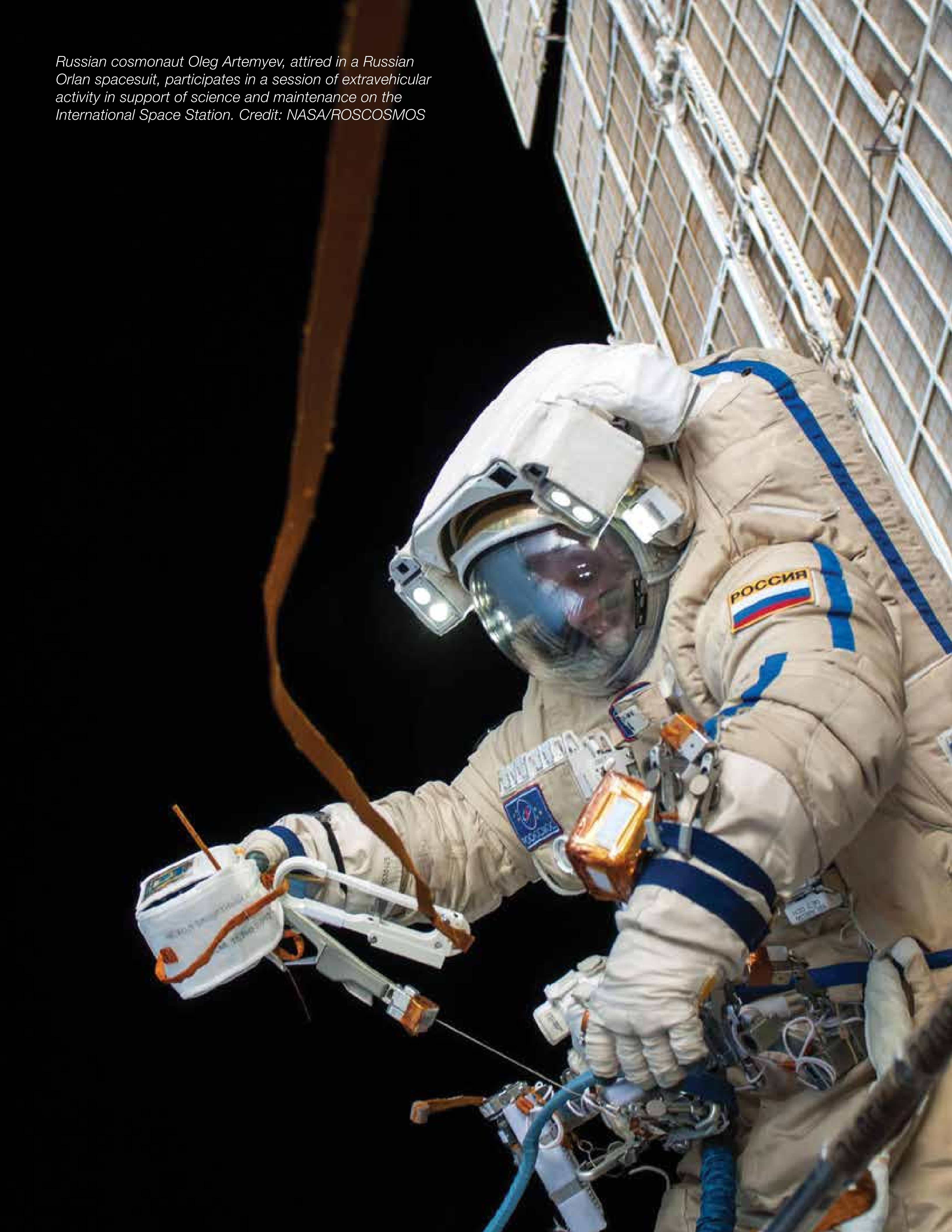
Many other studies are working to identify and mitigate other potential challenges of long-duration space missions. The CSA's Vascular series of studies analyzes the effects of weightlessness on astronauts' blood vessels and hearts, including how arteries react to changes in blood pressure and whether insulin resistance occurs during spaceflight. The NutrISS investigation, a collaboration of ESA and ASI, has taken a closer look at ideal body composition to avoid an increase in the fat-mass-to-lean-mass ratio due to inactivity from microgravity.

In addition to benefiting future exploration missions, station research on human physiology is also generating benefits on Earth. ESA's Airway Monitoring research studied the occurrence and indicators of airway inflammation in crew members due to dust in spacecraft. The methods used to gather those data have contributed to the development of rapid, non-invasive lung tests for an improved quality of life—both on Earth and in space.

When scientists complete an experiment aboard the International Space Station, the utility of that work has just begun. Space station partners have worked to maximize the impact of scientific research being conducted on board. Repositories like the JAXA-sponsored Integrated Biobank for Space Life Science (ibSLS) were established to connect space and ground research and provide a wealth of historical data. NASA's GeneLab contains decades of experimental biological data generated by spaceflight and corresponding ground experiments beginning in 1995. It is a one-stop source for all the genomic, transcriptomic, and other molecular data on cellular-level responses of terrestrial biology to the space environment. Numerous scientists use these data, including a research team that published results indicating altered gravity caused subtle changes in about 1,000 genes involved in the nervous system and controlled by insulin-related metabolic functions. That result suggests changes in the nervous system could be important in astronaut response to prolonged spaceflight.

In total, space station researchers have generated over 2,000 peer-reviewed publications (as of Sept. 2021) representing the work of more than 4,000 research investigators. With over 20% of those publications occurring in 2021, the third decade of continuous human presence aboard the station is already shaping up to be one of multiplying results.

Russian cosmonaut Elena Serova installs the Plasma Kristall-4 apparatus in the Columbus module. The mass of the experimental part of the apparatus is over 100 kilograms (220 pounds) on Earth. Credits: ROSCOSMOS/ESA



Russian cosmonaut Oleg Artemyev, attired in a Russian Orlan spacesuit, participates in a session of extravehicular activity in support of science and maintenance on the International Space Station. Credit: NASA/ROSCOSMOS

Benefits of an Orbiting Laboratory

Generating benefits from the International Space Station

Throughout this book, you will find examples of benefits derived from your orbiting laboratory. Examples range from the tangible, such as air purification and water filtration products, to the potential, such as cleaner combustion engines or medical scans that expose patients to lower levels of radiation. Some benefits arise from new scientific knowledge while others are derived from the specialized equipment needed to live in and conduct research in space. In communicating the array of benefits stemming from the International Space Station, it's useful to sort them into four broad categories: scientific, societal, exploration, and economic.

Scientific benefits stem from knowledge gained through the growing volume of research conducted aboard station. Entering its third decade of life, the International Space Station has evolved into a robust scientific laboratory with dozens of research facilities and an array of tools and observational instruments. The space station has served as a platform for testing and validating new instruments and techniques for use in space. It has also served to refine processes for training crew and supporting them in real time as they act as the surrogate eyes and hands of scientists conducting research across every discipline of science. Additionally, engineers have gained experience designing hardware that enables experiments to run autonomously or with minimal crew interaction. As a result, both the amount of research that can be supported simultaneously and the fidelity of results has grown dramatically over the station's first two decades of operation.

At any one time, this microgravity lab hosts hundreds of investigations spanning every major scientific discipline. External instruments gather data relevant to studies from astrophysics to climate change. Inside the station, experiments are conducted in fields as far ranging as microbiology and metallurgy. The data collected are forming new areas of scientific research, providing novel insights that cannot be obtained on Earth, and giving us a better understanding of our universe. Many examples of new discoveries and new scientific knowledge fill the pages of this book.

Societal benefits range from medical advancements already improving our lives here on Earth to intangible contributions to our global society. From neonatal care to robotic surgery, research on the station has helped create technologies used in hospital settings today. Station research has generated a more detailed understanding of the complex structures of proteins involved in disease, leading to new medical treatments and a greater understanding of many illnesses.

On the less-tangible side, station research has fostered scientific cooperation around the globe with researchers representing more than 100 countries. The space station also has helped inspire the world's next generation of scientists and engineers. Station crew, both cosmonauts and astronauts, have connected with millions of school children through amateur radio contacts, live video downlinks, and recorded science demonstrations. Teachers connect their classrooms with the orbiting laboratory through story-time readings recorded on orbit, detailed science lesson plans, citizen science opportunities, and even flight opportunities for student-developed experiments.

> "Entering its third decade of life, the International Space Station has evolved into a robust scientific laboratory with dozens of research facilities and an array of tools and observational instruments.

Exploration benefits derived from an orbiting platform are clear: it's the ideal test bed for demonstrating and improving technologies needed to explore farther into space and stay there longer. New power generation, air and water recycling, carbon dioxide removal, communications, and computing systems are among the exploration-enabling technologies that have been tested, proven, and continue to be improved using the station. Researchers also study how humans adapt psychologically to working in space, how best to grow plants for long-duration space missions, and more.

Supporting a continuous human presence in space has helped develop processes for preparing crew for long-duration missions in microgravity and mitigating any negative physical effects such as bone and muscle loss. Processes for supporting crew members as they conduct spacewalks for routine maintenance, replacement of worn-out parts, and even unscheduled repair of complex systems have benefited from lessons learned. They have been refined, tested, and refined again over more than two decades.

Economic benefits are derived from the new products and services resulting

Students from Arkansas State University show off a wax moth larvae prior to the launch of their investigation to study how effectively the larvae can digest plastic waste materials in microgravity. Credit: Arkansas State University

from space station activities. Examples of products available for purchase today range from robotic gloves to medicines and medical devices.

The station also has served as a business incubator, supporting the growing space economy by transferring the operational experience of governmental space agencies to a growing number of space-focused companies. This knowledge transfer has contributed to a rapid expansion of the space marketplace. New launch providers and launch capabilities support station supply lines while also driving down the cost of accessing space. As those costs go down, new telecommunication and observation services are emerging from flocks of small satellites in low-Earth orbit.

Today, more than 30 commercially owned and operated facilities on station support researchers. A cadre of commercial payload developers helps scientists translate their research ideas into hardware for launch to and safe operation on the station. Some of these companies now are applying that experience to demonstrate technologies for manufacturing in space. Fiber optics with much greater data transmission characteristics and artificial retinas for restoring vision are just some products that soon could be made in space.

Other companies are building the business case and generating designs for new commercial platforms in low-Earth orbit. Such specialized stations soon could host dedicated manufacturing facilities, future research laboratories, and even future space tourists.

As shown throughout this book, the International Space Station continues to generate numerous benefits that improve individual lives on Earth, inspire the next generation of scientists and engineers, foster international collaboration, and enable future exploration deeper into the solar system. Knowledge is being generated in scientific fields from cell biology to cosmology. New technology is being developed and demonstrated with applications as wide ranging as communications, power generation, agriculture, and medicine. With two decades of operations behind it, the orbiting laboratory is producing a legacy that will be felt for decades to come.

Image of a drop of insulin solution contained by surface tension in the Ring Sheared Drop (RSD) device. The RSD investigation studies protein aggregates called amyloid fibrils that play a role in diseases such as Alzheimer's, Parkinson's, prion, and type 2 diabetes. Credits: Joe A. Adam and Patrick M. McMackin

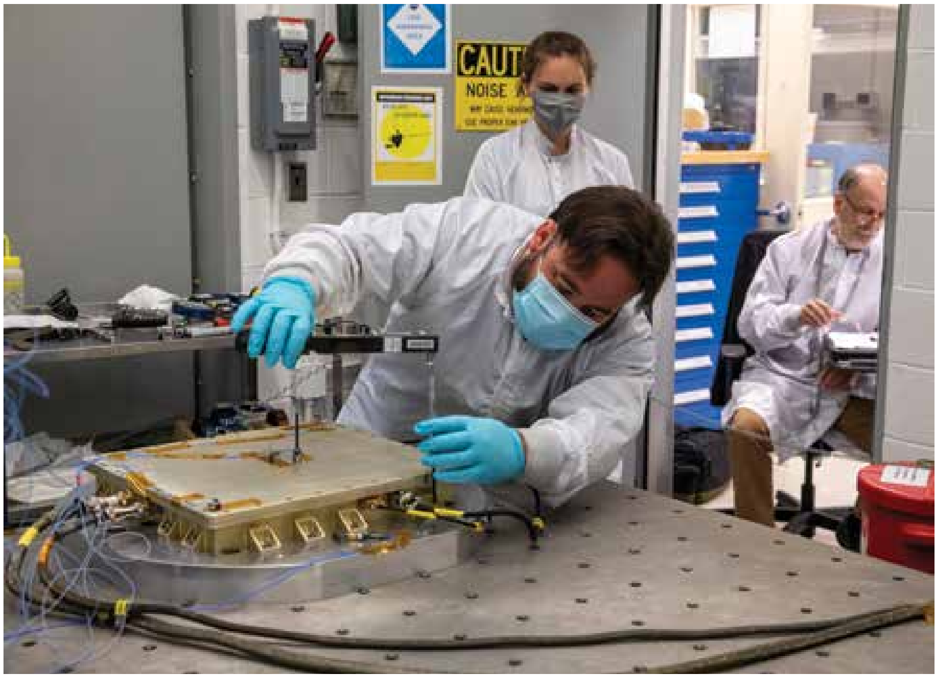
Building on Past Success

Using two decades of operational experience and research results to make the third decade even better

The past 20 years saw the station evolve from an outpost on the edge of space into a highly capable microgravity laboratory. Thanks to the more than 3,300 investigations conducted to date, the station has established a firm base of research knowledge and operational know-how. Now results are compounding, new benefits are materializing, and innovative research and technology demonstrations are building on previous work.

While new areas of science are still being explored, researchers are using the experience and knowledge gained from past research to propose new experiments and design better systems to support future space missions. New facilities are being installed, often based on experience gained from older ones, to handle growing interest from the scientific community. Veteran station researchers are flying experiments based on insights gained from their first flights or other space station investigations. Teams of researchers are combining their knowledge for novel results.

Recent studies have pushed the potential of protein crystal growth experiments further with the addition of real-time monitoring and adjustments to experiments. Launched in Feb. 2021, the Real-Time Protein Crystal Growth 2 experiment gives scientists the opportunity to monitor and optimize protein crystal growth in microgravity through real-time communication with space station crew members. Astronauts can check the crystals, report on their growth, and make changes based on initial observations.



NASA Langley technician Dave Mclain tests hardware for the CLARREO Pathfinder mission. Credit: NASA/David C. Bowman.

New approaches such as the use of tissue chips are opening unexplored areas of research. Tissue chips are small models of human organs containing multiple cell types and were first sent to the International Space Station in 2018. After several successful demonstrations validating their use, many are getting their chance at a second flight. These chips may make it possible to identify safe and effective drugs or vaccines much more quickly than the standard process.

Researchers investigating the mechanisms of certain diseases on Earth must contend with the forces of gravity and the interaction between liquids and solid containers. These forces differ from interfaces in the body they are attempting to model, such as those in arteries and brain tissue, and can affect results.

The Ring Sheared Drop experiment team developed another innovation benefiting medical research. This specialized device uses surface tension rather than a solid container to hold liquids in microgravity. The device pins a drop of liquid between two rings and rotates one while keeping the other stationary to create shear flow, or a difference in velocity between adjacent liquid layers.

Previous research shows that this shear flow plays a significant role in the formation of amyloid fibrils associated with neurodegenerative diseases such as Alzheimer's. Results could improve scientists' fundamental understanding of how amyloid fibrils form and are transported, as well as the effects of shear at fluid interfaces relevant to conditions in the body.

Earth science research aboard the International Space Station will also be getting an upgrade with the planned launch of CLARREO Pathfinder. Researchers behind this project previously designed and launched the Total and Spectral Solar Irradiance Sensor (TSIS-1), an external space station instrument tracking solar irradiance. Solar irradiance, the total energy flowing into Earth from the Sun, is a crucial parameter for climate modeling and is represented by one of the longest climate data records derived from space-based observations. TSIS-1 has allowed researchers to maintain continuity of that record.

By applying the knowledge gained from the design and implementation of TSIS-1, the creation of CLARREO was much more streamlined. Once installed on the station, CLARREO will study Earth's climate by taking measurements of sunlight reflected by Earth and the Moon with five to ten times lower uncertainty than measurements from existing sensors.

The Atmospheric Waves Experiment (AWE) will focus on colorful bands of light in Earth's atmosphere called airglow to determine what combination of forces drive space weather in the upper atmosphere. AWE is the first dedicated NASA mission designed specifically to characterize the properties of global mesospheric gravity waves.

Fluid physics research has benefited greatly from the availability of a microgravity research laboratory, building significantly on the science community's knowledge of the topic since April 2004 when the first Capillary Flow Experiment (CFE) was conducted onboard the orbiting lab. The work began as a series of fundamental fluid physics investigations that led to patents that involve technology applications associated with space exploration such as thermal control systems and liquid fuel tanks.

Since the completion of those initial fluid physics studies, the International Space Station has provided a unique venue for exploring the nature and application of fluidics, leading to dozens of scientific publications and multiple patents. For example, researchers are using station as a platform to study nanofluidics to create a novel drug delivery mechanism—a refillable implant, placed just under the skin that administers medicines at pre-determined dosages for weeks or even months between refills without any moving parts. One application of this implant is in clinical trials and could be approved for use soon.

ESA has also performed microgravity fluids research, contributing greatly to our understanding of boiling, heat transfer, and fluid flows. Their Multiscale Boiling experiment analyzed bubbles that form during boiling. Without gravity, boiling takes place in slow motion and produces larger bubbles. Multiscale Boiling allows scientists to observe and measure effects that are too fast and too small on Earth, thus getting a more complete understanding of heat transfer during the boiling process. This information could be applied to help cool electronics like laptops more efficiently.

Looking forward, ESA plans to launch a new facility to station that will build on the results of Multiscale Boiling. The new Heat Transfer Host facility intended for launch to station in a few years will contain a series of experiments designed around the Multiscale Boiling data.

ROSCOSMOS launched the first bioprinter, Organ.Aut, to the space station, kicking off a new area of research that could one day lead to the creation of organs for use in transplants. The printer was used to culture cartilage cells in space using a magnetic field. U.S.-based company Redwire Space's BioFabrication Facility (BFF) further explored the possibility of printing human tissue in orbit. Redwire expects to continue testing the in-orbit manufacture of cardiac and orthopedic tissue and start a new program aimed at testing the manufacturing of vasculature in space.

A JAXA investigation, Space Organogenesis, took a different approach to trying to solve the organ shortage. Researchers tested using human stem cells to grow 3D organ buds aboard station. Organ buds are condensed masses of tissue that eventually develop into full organs. Researchers plan to observe growth of the organ buds and analyze changes in gene expression and, ultimately, establish the technology for cell growth in three dimensions in space.

New commercial facilities are further expanding research capabilities to support future efforts in low-Earth orbit. The Bigelow Expandable Activity Module (BEAM) is an experimental expandable space station module developed by Bigelow Aerospace and attached to the International Space Station in 2016. Following its successful year-long demonstration of this technology, it entered service as a storage module on station.

The Bishop Airlock, constructed by Nanoracks, was launched in 2020. It is the first commercially owned and operated station airlock. The airlock allows movement of larger payloads inside and outside the station, increasing the station's capacity to deploy small satellites.

Coming soon, U.S.-based company Axiom plans to launch the first habitable commercial module to be attached to the space station. This project will demonstrate the ability of commercial entities to provide products and services in space, furthering the transition to a sustainable low-Earth orbit economy in which NASA is one of many customers. In 2022, Axiom launched the first fully private crew of astronauts to the space station where they spent more than a week conducting their own research investigations.

The space station is preparing for extended years of operation through additional installations of new ISS Roll-out Solar Array (iROSA). Based on technology previously demonstrated on station, iROSA is made up of compact arrays that open like unrolling a long rug. The first pair of arrays were installed in 2021 with the next set launching in 2022. The combination of the eight original, larger station arrays, and the smaller, more efficient new arrays will provide a 20% to 30% increase in power for research and operations. The roll-out arrays are also a technology demonstration that will benefit future missions. For example, the same solar array design will be used to power elements of the Gateway lunar-orbiting outpost.

The station's regenerative life support hardware provides clean air and water for station crews. Planned upgrades to the system will demonstrate technology that could get spacecraft to the level of reusability needed for deep space missions. The Universal Waste Management System (UWMS), a newly designed space toilet, is being tested for future use aboard Orion for the Artemis II flight test that will send astronauts beyond the Moon and back. This toilet addresses crew feedback about comfort and ease of use. Improved integration with other components of the space station water system will aid in recycling more urine. It also features a 65% smaller and 40% lighter build than the current space station toilet, saving valuable mass and volume for future exploration missions.

An upgraded distillation system for the space station's Urine Processor Assembly was also tested in 2020. The station's previous system suffered an issue common to many machines—deteriorating belts. With upgrades included in the latest iteration, engineers anticipate a service life of more than 4,300 hours without parts replacement, compared to 1,400 hours.

As the International Space Station enters its third decade of use, scientists continue lining up to initiate new research efforts. Engineers are proposing new technology demonstrations and upgrading existing systems to increase reliability and reduce their mass, volume, and maintenance needs in preparation for missions farther into space.

With more follow-on experiments building on past results, and new research facilities entering service each year, many more years of technological, scientific, and commercial breakthroughs will follow.

ESA astronaut Luca Parmitano installing the MultiScale Boiling Experiment Container (EC) in the Fluid Science Laboratory (FSL) in the Columbus Module. Credits: NASA/ESA

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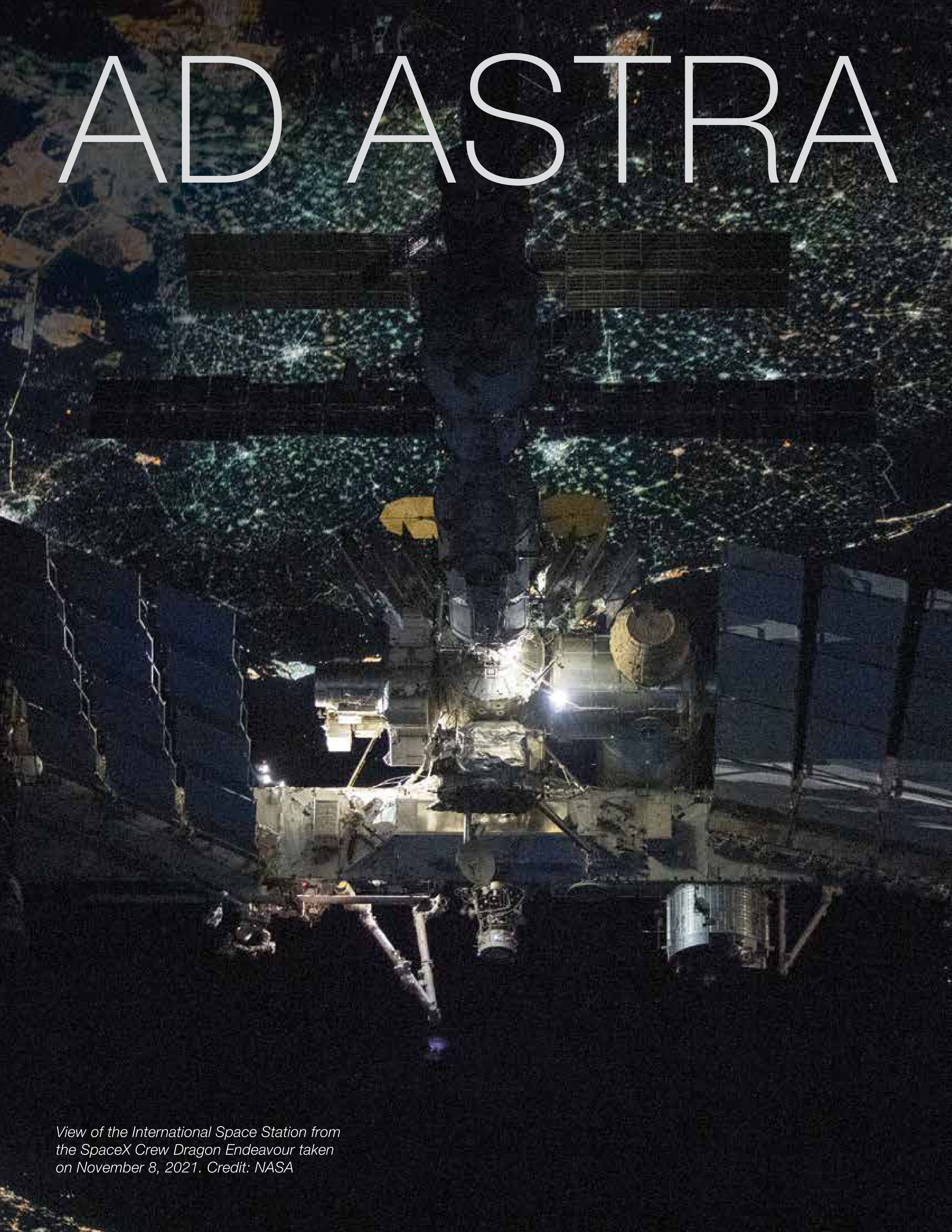


View of the International Space Station from the SpaceX Crew Dragon Endeavour taken on November 8, 2021. Credit: NASA

Future Plans for the International Space Station

Perspectives from the space station partnership

Having entered its third decade of service, the sponsoring partners of the International Space Station are once again considering extending operations. This time to 2030. Originally scheduled for a 15-year mission, the station will have doubled its originally planned length of service by that time. As illustrated by the many examples of research accomplishments found in this book and the plans discussed by the partnering space agencies in this article, the third decade of station activities will indeed be one characterized by increasing research results.

Canadian Space Agency

Canada entered the space program in 1962 with the launch of the Alouette 1 satellite into low-Earth orbit. Following the development of the original Canadarm for the space shuttle, the first Canadian astronaut launched into low-Earth orbit in 1984. In 1988, Canada joined the International Space Station Program. CSA has supported the station's construction and operation through sophisticated robotic systems including the Mobile Base, Canadarm2, and Dextre. This contribution led to the participation of Canadian scientists and engineers in 78 station investigations, including seven technology demonstrations and 12 educational and cultural activities between 2000 and 2019.

Research and development aboard the space station is now an important component of the Canadian Space Strategy published in 2019. Using this experience in space science and technology, Canada will continue to use the station to pursue the following goals: 1) advancing human space exploration by conducting health research and supporting technology development leading to socio-economic benefits and commercialization of new products; and 2) inspiring the next generation of Canadians to pursue an interest and studies in science, technology, engineering, and math (STEM).

So far, Canada's space activities have benefited space exploration through the development and demonstration of a wide variety of technologies such as robotic manipulators, neutron dosimeters, wearable physiologic sensors, and biomedical analytical instruments. These instruments and technologies have been validated in the microgravity environment of low-Earth orbit and have demonstrated their functionalities and usefulness for future space missions. Scientific knowledge generated through Canadian investigations are detailed in this document. By increasing our understanding of the impact of the space environment on human physiology and psychology, Canadian researchers have contributed to improving crew safety on future missions into deep space. Canadian utilization of space station resources will continue with this momentum to prepare humanity for the next steps of space exploration.

Past activities have brought social benefits back to Earth. Important examples are advances in health sciences and medicine. Canada's involvement in the International Space Station Program has led to a better understanding of a number of space health challenges and advanced the development of related biomedical devices. As described in this new edition, R&D in space robotics has led to applications in healthcare and industrial manufacturing. Future Canadian activities related to the program will continue on this trend and will generate socio-economic

2017 Canadian Space Agency astronaut team. Back: Jenni Sidey-Gibbons. Front, left to right: David Saint-Jacques, Joshua Kutryk, Jeremy Hansen. Credit: NASA/Bill Stafford benefits such as knowledge translation, industrial applications, training of highly qualified personnel, and development of new technologies that benefit the Canadian population and humanity.

In 2016, the Canadian Government provided support for Canada's continued participation in the space station and secured future Canadian astronaut flights to this unique international laboratory. Space is the most exciting laboratory imaginable in which to inspire a new generation of Canadians in the pursuit of science, discovery, and technological advancement. Space capabilities will also play a central role in developing and supporting emerging technologies. Canada is now involved in discussions with the space station's international partnership on utilization beyond 2024 to maximize the benefits of space station research and development activities and to continue to open the way to space for all humanity.

European Space Agency

The space station international partnership recently celebrated 20 years of continuous operations. Those past 20 years of continuous human presence on station have resulted in a record of operations and utilization that have paved the way for many new inventions and opportunities. The International Space Station is now entering possibly its last, but potentially golden, decade of use with increased crew time, increased capabilities, and upgraded infrastructure. During this decade of operations, the station shall continue to be an essential and integral component of space research and shall continue to serve as the world's leading laboratory for cutting-edge research and technology development that will enable human and robotic exploration of the Moon and Mars, advancing critical capabilities that will take humans farther into space and reduce the cost of human spaceflight.

> "The space station international partnership recently celebrated 20 years of continuous operations.

While international partners prepare for the next chapter of human exploration, it is critical that we learn from those experiences. But we must also recognize the limits of that experience. A lot remains to be understood about the physiological and performance effects related to exposure to spaceflight hazards such as radiation, altered gravity, and hostile environments. The same is true when considering the unique challenges of providing medical and behavioral health support critical to successful human exploration of deep space.

To this end, it is important that the International Space Station partnership continues to maintain and, where feasible, upgrade station capabilities to ensure efficient operations and utilization until the station's end of lifetime. ESA has initiated (and will soon complete) "Columbus 2030" activities, which aim to enhance and expand on-orbit infrastructure, thereby increasing space station utilization while reducing operational costs. Columbus 2030 will modernize the European Columbus module's information technology infrastructure (including ground and support infrastructure), allowing more efficient station operations. New infrastructure elements will be added, such as the European Drawer Rack Mk2, the European Transport Container-Replacement, Live Cell Imaging, and upgraded Biolab capabilities including a 3D bio-printing and 3D cell culture facility, to name a few. Furthermore, inflight technology demonstration activities (e.g., advanced life support systems like ANITA-2 and 3DMetalprinting) will continue to translate space station research into space exploration technology systems that enable exploration missions to the Moon, Mars, and eventually deep space. The station will therefore continue to provide unparalleled opportunities for scientific research and translation, and technology demonstration and validation, and will continue to serve as a staging post for preparation for long-duration exploration missions, advancing critical capabilities to take humans further into space (ad astra!) and also reducing the cost of human spaceflight.

Italian Space Agency

The Italian Space Agency (ASI) Human Space Flight Program has the specific objective of gaining knowledge through space research and transferring it to biomedical and technological applications on Earth, as well as to relevant applications for human exploration of space.

The primary goals of this program are:

- To understand life processes and adaptation mechanisms associated with long-term stays in the space environment.
- To sustain a human program of exploration in the solar system and beyond.
- To foster the integration of multi-disciplinary expertise, both scientific and industrial, for programs of high-level technology transfer.

ASI provides access to different space platforms, thanks to cooperative agreements with ESA (E3P) and NASA (MoU ASI/NASA). New national initiatives and international collaboration perspectives are being nurtured. The aim is to define a path for Italian research activities that build upon and consolidate previous results and contribute to international goals. The program focuses on the following research areas, which require specific facilities and flight opportunities:

- Life sciences, and particularly macro-areas such as integrated physiology, microbiology, plant biology, and bio-regenerative life support systems, radiation.
- Physical sciences and especially fundamental, material, and fluids physics.
- Technological demonstrations and commercial developments.

Studies in these areas are encouraged because of their connection to future human exploration scenarios.

The majority of ASI experiments focus on biology and biotechnology, human physiology and technology demonstration. So far ASI has carried 73 experiments aboard the International Space Station, 69 of which have been implemented thanks to the Memorandum of Understanding between ASI and NASA, three in the frame of the ESA's National Contribution program and one by virtue of a specific agreement with ROSCOSMOS.

During the last mission of an Italian astronaut, Luca Parmitano, ASI brought six new experiments on board the station, four of which are still operational. The next challenge for ASI is represented by Samantha Cristoforetti's mission in 2022, for which ASI is launching a group of new experiments.

For the purposes of composing the new utilization plan, ASI has recently selected a list of new experiments, mostly of biology, human physiology, and technological demonstration. These experiments will be gradually launched over the next few years.

In parallel, ASI is among the promoting agencies of the ISS4Mars project. ISS4Mars is an international proposal to use the space station as an analog platform to support the next steps for human exploration. The International Space Station is the only possible available integrated analogue for a mission to Mars where the impact of all space conditions, even if approximately, can be simultaneously mimicked. The utilization strategy shall focus on solving the still-open research questions and technology gaps necessary for deep space exploration. The feasibility study of this project is underway.

Japan Aerospace Exploration Agency

JAXA continues to encourage use of the ISS Kibo module for a broad range of activities to maximize benefits to the Japanese economy and add to the significant contributions already made toward scientific and technological discovery. Kibo's external platform is home to many Earth and deep space observation instruments as well as space exposure experiments, while the Japanese Experiment Module (JEM) airlock continues to support small satellite deployments. As one example, HISUI (Hyper-Spectral Imager Suite) developed and operated by Japan's Ministry of Economy, Trade and Industry (METI) has been active since 2020. It collects Earth observation data that are useful for mapping the location of mineral deposits for potential extraction, identifying plant distribution for environmental studies, and tracking soil condition for agricultural uses.

Internal facilities provide one-of-a-kind opportunities for researchers. For example, Mouse Habitat Units allow biologists to study physical adaptations to partial and microgravity conditions. The Electrostatic Levitation Furnace provides materials scientists with the ability to conduct research on materials at very high temperatures without concern for contamination from containers.

As many examples in this book illustrate, JAXA has focused the use of Kibo facilities for drug design, aging research, small satellite orbital deployment, and space environment exposure by academic, commercial, and public entities worldwide. JAXA aims at consistently achieving 30% to 50% commercial utilization for these purposes by 2024. A growing number of collaborations between JAXA and user-service providers continues to fuel the formation of new organizations and groups that independently provide high-quality services for users of Kibo facilities. As these partnerships deepen, operational know-how continues to be passed along, expanding new markets in low-Earth orbit.

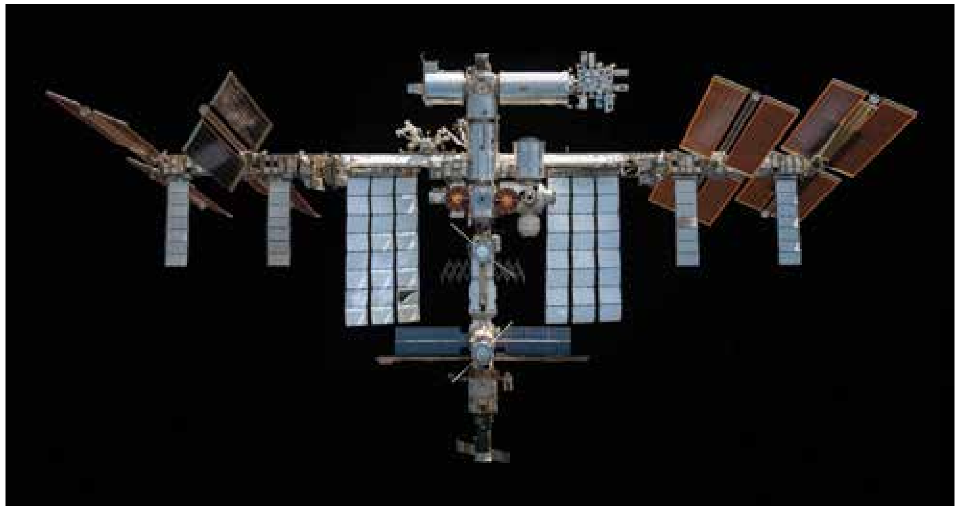
Commercially, JAXA has partnered with companies such as PeptiDream Inc., and Sony Computer Science Laboratories (Sony CSL) to provide new pathways for research and technology development. Furthermore, to promote diverse partnerships using the space station, JAXA has invited Asian and Pacific nations to participate in the use of Japanese facilities. For example, an agreement with Singapore enabled the use of the JEM Small Satellite Orbital Deployer (J-SSOD) to launch a Singaporean satellite that tested new thruster technologies for use with small satellites.

JAXA continues to focus on promoting strategic partnerships to commercially establish the research and development testbed aboard the Kibo module, building on successful fee-based agreements such as that with the Japanese drug discovery company, PeptiDream Inc. That agreement enabled more frequent launching of samples, increasing the number of tests performed in Kibo, which accelerated the development of new drugs while reducing overall research costs. Furthermore, the company can expand Kibo utilization in its collaborative research activities with other entities. Such benefits strongly appeal to potential candidates of commercial users who have already participated in the Kibo experimental programs since 2013, including Chugai Pharmaceutical Co., Ltd. and Taiho Pharmaceutical Co., Ltd. JAXA has selected Space BD Inc. as a private business operator and has established a system to develop customers and operate experiments in the private sector by using some of the experiment opportunities.

The Space Exploration Innovation Hub program by JAXA created another successful partnership with Sony CSL. JAXA's already-existing, IVA-replaceable Small Exposed Experiment Platform (i-SEEP) on the Kibo Exposed Facility will play a key role in establishing a mass-data communication system between multiple satellites or a satellite

and a ground operation interface. This innovation is also widely open for future longer-distance optical fiber communication on the ground.

In closing, the sustained use of the International Space Station and the Japanese Kibo module to their full extent through 2030 shows significant promise for continued scientific, innovative, and economic developments.



The International Space Station pictured on Nov. 8, 2021. Credit: NASA

International Space Station National Laboratory

Moving into its third decade of continuous crewed presence, the space station is now transitioning from an era of utilization to one that builds on past outcomes to establish the robust low-Earth orbit economy of the future. Results from the last 20 years of research and technology development on the space station have shown the unique, tangible benefits that such development in the low-Earth orbit environment offers. Now, the ISS National Lab plays a crucial role in demonstrating the economic value of space-based research and development, and in driving a sustainable market in low-Earth orbit. To achieve this, the ISS National Lab works to increase demand among industry users. It fosters supply-side growth by supporting a growing number of companies and organizations that provide services related to payload development. Finally, it works to attract private-sector investment into the low-Earth orbit economy.

For the past 10 years, the ISS National Lab has been managed by the Center for the Advancement of Science in Space, Inc. (CASIS). In this time, more than 500 ISS National Lab-sponsored payloads, representing more than 600 investigations, have launched to the space station. Almost 70% of these payloads represents research and development from the private sector to advance commercial products and spur economic development. Fortune 500 companies that have leveraged the ISS National Lab include Procter & Gamble, Merck & Co., Adidas, Colgate-Palmolive, Target Corp., Lockheed Martin Corp., and Hewlett Packard Enterprise, among many others. To date, more than $240 million in external, non-NASA funding has been committed in support of ISS National Lab-sponsored investigations. Additionally, through a multiyear partnership with Boeing, the ISS National Lab supports innovative startups through the MassChallenge Technology in Space Prize. Since its inception in 2013, the prize has provided $8.8 million in funding to 27 start-ups for ISS National Lab-sponsored research and development.

Through knowledge gained in the last decade, the ISS National Lab has identified key areas of research and development with the most potential to provide economic value and lead to the production of commercially relevant products. ISS National Lab Research Announcements now target these strategic areas of focus, which include technology development and demonstration and in-space production applications in advanced manufacturing and materials as well as tissue engineering and biomanufacturing. The ISS National Lab has also established multiyear partnerships with other government agencies, including the National Institutes of Health (NIH) and the U.S. National Science Foundation (NSF), which together have provided more than $35 million in funding to support nearly 50 ISS National Lab-sponsored investigations. In the last 10 years, more than 150 peer-reviewed articles have resulted from ISS National Lab-sponsored research and development, lending credibility and prestige to research conducted on the space station.

On the supply side, the ISS National Lab provides funding and support to a diverse group of more than 35 Implementation Partners that offer services to aid investigators in translating ground-based concepts into flight-ready payloads. To facilitate business-to-business relationships, the ISS National Lab uses an online portal to connect Implementation Partners with investigators that can use their services. The ISS National Lab also provides access to and creates demand for an increasing number of commercially operated facilities on the station that serve to expand the in-orbit capabilities available to investigators. Currently, 18 space station facilities are owned and operated by 10 Commercial Service Providers (a subset of Implementation Partners).

Utilization of the ISS National Lab is also generating substantial investment. Both the awarding of, and subsequent flight of, ISS National Lab-sponsored investigations are key indicators of economic value creation for start-up companies. Since 2014, start-ups that have completed projects sponsored by the ISS National Lab have collectively raised more than $1.1 billion post-flight. These funds were raised from public equity markets and venture/private capital, and via public and private grants. Additionally, the ISS National Lab has established an Investor Network that currently includes close to 250 members. Through this network, the ISS National Lab has facilitated nearly 1,000 introductions to date in support of capital-raising efforts in the ISS National Lab ecosystem.

Advancing science literacy in the future workforce is also central to the mission of the ISS National Lab. Leveraging the space station as a powerful platform for education, the ISS National Lab is helping to shape the next generation of innovators and leaders that will play a key role in ensuring the success of the future low-Earth orbit economy. The ISS National Lab partners with 25 educational programs that are part of the Space Station Explorers community, and in fiscal year 2021 alone, nearly 3.8 million people engaged with these programs.

Building on the strong foundation established over the past decade, the ISS National Lab will continue to work with NASA and International Partners to accelerate growth and investment in the low-Earth orbit marketplace. The successes achieved so far have paved the way for a sustainable and robust low-Earth orbit economy of the future, where multiple platforms and a space-based national laboratory will support both government and commercial research and development that provides valuable benefits to our nation and the world.

National Aeronautics and Space Administration

On November 2, 2020, NASA marked 20 years of continuous United States human presence in low-Earth orbit onboard the International Space Station. Research and technology demonstrations aboard the space station have provided the foundation for extending human presence beyond low-Earth orbit into deep space, while two decades of continuous 24/7/365 operations have generated expertise and insights that can only come with experience.

As the world's first truly international orbiting laboratory, the space station continues to represent an unparalleled capability in human spaceflight. Scientific investigations from the quantum realm to the cosmological nature of our universe, and at every scale in between, have pushed the frontiers of knowledge in every major discipline of science. Earth-observing instruments mounted externally have generated unique datasets, helping scientists improve climate and ocean modeling. All this knowledge has the potential to benefit life here on Earth while enhancing the competitiveness of U.S. private industry.

The international partnership created through the ISS Program and its accomplishments exemplify how countries can work together to overcome complex challenges and achieve collaborative goals. Indeed, more than 100 countries have used, or are currently using, the orbiting laboratory. However, the experience gained in more than two decades of collaborative operations of five space agencies, representing 15 ISS Intergovernmental Agreement signatory nations will be a lasting legacy, providing a framework for collaborative exploration efforts for decades to come.

The International Space Station is a stepping-stone for NASA's Artemis program that will land the first woman and person of color on the Moon. As the only place for conducting long-duration research on how living in microgravity affects living organisms, especially humans, as well as testing technologies to allow humans to work at the Moon, the space station serves as a unique asset in the effort to establish a sustainable presence at the Moon. We have tested important technologies for the Artemis program on station ranging from life support systems to radiation sensors.

Looking forward, NASA's vision for low-Earth orbit is a sustained commercial space marketplace where NASA is one of many customers. The development of a healthy commercial supplier base for low-Earth orbit activities is critical to achieving that vision. Today, the space station is already enabling commercial cargo and crew transportation that industry is working to make more cost-effective. More than a dozen commercial research facilities are in active operation onboard the station while more than 20 companies provide payload development and integration services in support of the International Space Station research community. NASA has also initiated the Commercial LEO Development program to further the development of private on-orbit capabilities beyond what is available today through the space station.

As we prepare for human exploration missions into deep space, it is important to reflect on the critical value of the proven partnership that has made the International Space Station possible, and to consider how to build on these relationships as humanity proceeds into cislunar space. It is necessary to maximize the value and impact of the space station today to allow users to explore new microgravity applications, test new markets, and communicate those success stories to stimulate broader interest in low-Earth orbit from non-traditional space users.

ROSCOSMOS State Corporation for Space Activities

ROSCOSMOS State Corporation for Space Activities supports the implementation of the Russian Federation space program. ROSCOSMOS responsibilities also include developing international cooperation in the space sector and creating conditions for using the results of space activities in Russia's social and economic development.

With more than 20 years of successful use, the development of the Russian Segment of the International Space Station (ISS RS) continues. In 2021, two new Russian modules, the multi-purpose laboratory module Nauka and the node module Prichal, launched and successfully docked to the ISS RS. The Multi-zone Electric Vacuum Furnace science hardware, which was included in the module, supports research activities to grow semiconductor crystals using replaceable heaters and processes for zone melting, bulk crystallization, and directional crystallization. The integration of the Nauka module enables an estimated increase of more than 17% in the quantity of research activities carried out on the ISS RS.

Processes to expand use of the ISS RS also continue to evolve. An organization formed under the auspices of ROSCOSMOS functions as an operator in providing commercial services to use the Russian Segment and enables interested organizations to fund such activities.

In cooperation with academic and commercial organizations from different countries such as Kazakhstan, United Arab Emirates, and Hungary, ROSCOSMOS continues to devote special attention to studying the influence of low-Earth orbit on human life support, plants, materials, and combustion processes, as well as the orbital deployment of satellites.

All these actions are directed at increasing research in various areas to generate significant results in scientific and applied research activities while maximizing the investment return and economic impact.

Seeing Our Home IN A Whole New Light

Earth observation taken by Expedition 59 crew.
Credits: David Saint-Jacques/CSA

> *“It was a very sobering perspective to get how fragile, unique, and sacred our spaceship Earth is, and the responsibility we have to be good shepherds of her.*
>
> *-CSA astronaut David Saint-Jacques*

Expedition 60 crew members take turns capturing images of rapidly intensifying Hurricane Dorian from the cupola inside the International Space Station on August 30, 2019, as it churned over the Atlantic Ocean. Credit: NASA

An Unmatched Eye on Earth

Helping farmers, cities, forests, disaster response, climate science, and more from orbit

On Earth, we often look toward the sky, longing to know what resides in the rest of the universe. Meanwhile, 402 kilometers (250 miles) above our planet, the International Space Station is looking back. That Earthward gaze is feeding data and imagery back to scientists, farmers, foresters, and others around the world, making a difference for humanity right now.

Multiple Earth-observing instruments ride on the exterior of the station above us, including a limb full of cameras, boxes, and tools that hangs off the station's Japanese Experiment Module. Earth-observing CubeSats regularly deploy from the station's airlock as well as some of its resupply vehicles. Inside the station, astronauts and cosmonauts take photos of the planet from the windows of the orbiting lab and conduct Earth science experiments. All this work provides insight into our planetary home and how we might prepare for coming changes.

"If you don't have a good understanding of how things might change, you are in a very poor position to be able to handle it when they do," says William Stefanov, manager of the Exploration Science Office at NASA's Johnson Space Center in Houston.

The factors influencing our climate must be tracked over long periods. With more than 20 years in orbit, and counting, the space station is a great place to collect such long-term data. The combined information creates a unique data set that helps us make informed decisions on Earth, and potentially develop solutions to environmental issues.

The space station affords a unique planetary perspective with an orbital path covering 90% of the Earth's population. Its position in orbit allows astronauts to see the Sun rise and set 16 times each day across the world.

"That orbit allows the space station to pass over different spots of Earth at different times of day or night and collect data. It is a fundamentally different data set than most other remote sensing instruments collect on free-flying satellites," says Stefanov.

International payloads on the outside of the orbiting laboratory, such as ECOSTRESS, GEDI, OCO-3, DESIS, TSIS (also known as TSIS-1), and HISUI, individually collect climate-related data. The MUSES Earth imaging facility even offers commercial access to a number of Earth observation tools. In combination, all these tools provide a unique set of measurements that could push the leading edge of environmental research.

Although some station experiments are focused on a specific application, many of these Earth-observing payloads provide data for a wide range of applications.

Analysis of the first six months of data from the State Space Corporation ROSCOSMOS (ROSCOSMOS)-Italian Space Agency (ASI) investigation UV Atmosphere - Mini-EUSO indicated that the multipurpose telescope was able to do everything from measuring variations in airglow and ultraviolet emissions from Earth to tracking space debris and cosmic rays. It has now completed more than 40 successful sessions. Part of JEM-EUSO, a larger program involving about 300 scientists from 16 countries who are working to enhance the observation of cosmic rays, the experiment is expected to measure artificial lights above land and oceans, study the impact of energetic cosmic radiation on the Earth's atmosphere, and register and track space debris in near-Earth orbits. Mini-EUSO has already measured several thousand faint meteor arrivals, allowing scientists to study these events and obtain data on arrival direction, velocity, and brightness.

Data from NASA's ECOSTRESS payload have also already had many applications. They have been employed in efforts to reduce heat absorbed by city surfaces, better allocate water, reduce fire risk, measure plant stress, search for geothermal energy sources, track mosquitos, help farmers efficiently water their fields, and more.

"ECOSTRESS measures small and subtle changes in temperature to identify plant stress, but those same measurements can also be used to identify extreme heat, such as that produced by fires or lava flows. We can also study movement of warm water currents and heatwaves in cities," says ECOSTRESS principal investigator Simon Hook. "With data that are valuable across so many science focus areas, researchers around the world are using ECOSTRESS data to produce really exciting results."

The U.S. Department of Agriculture, thousands of farmers around the world, and numerous water agencies now rely on these data for determining how much water their crops need, which ones are most water-efficient, and which ones are not getting enough water, even before they show visible signs of dehydration. A Los Angeles City pavement project has used the data to monitor the effectiveness of new reflective pavements installed to reduce heat. Forest managers can thin areas of stressed trees to reduce fire risk or at least mobilize fire crews in those areas during high-risk times.

"ECOSTRESS is a small, low-cost mission that has brought together so many scientists with different areas of expertise," says Hook. "But the core team is very small and has done incredible work."

Annmarie Eldering, project scientist for OCO-3, speaks during a What's On Board science briefing at NASA's Kennedy Space Center in Florida on April 29, 2019. The briefing was held for SpaceX's 17th Commercial Resupply Services (CRS-17) mission to the International Space Station, which launched OCO-3 into orbit. Credit: NASA/Kennedy Space Center

The ECOSTRESS team is even looking at collaborating with the research teams of other space station research payloads to provide additional benefits.

"The OCO-3 team wants to understand plants and their role in the carbon cycle," says OCO-3 project scientist Annmarie Eldering of NASA's Jet Propulsion Laboratory in Southern California. "It turns out our space station neighbor ECOSTRESS is looking at how plants respond to stress. And then there is GEDI, which is looking at how much plant material is on the ground. Scientists who are thinking about plants and their role in the carbon cycle are super excited. We have heard lots of discussion about how we can use all the data together to better understand plants."

NASA's OCO-3 sensor uses sunlight reflections through the atmosphere to measure variations in atmospheric carbon dioxide, observing changes of less than a single part per million.

"Most gases like ozone, carbon monoxide, or water vapor double or triple in atmospheric concentration when they are polluted, so it is pretty easy to detect. But for carbon dioxide, it is uniquely difficult to see the changes," says Eldering.

Measuring those small changes could be key to answering long-standing questions about atmospheric carbon dioxide.

"Fortunately for us, the plants and ocean absorb about half of human-generated carbon dioxide emissions every year. But there are still mysteries around how they do that, why the amount is different each year, and how absorption is going to happen in the future," says Eldering. "Our data are meant to help answer those kinds of questions."

In 2021, using data from OCO-3, researchers released one of the most accurate maps ever made from space of the human influence on carbon dioxide in the Los Angeles metropolitan area. These types of data help decision makers choose the most effective policies to reach goals for cutting emissions and measuring the effectiveness of new regulations.

"Now we're looking at a lot of other cities," said Eldering. "And when you look at our data as well as other gases that are measured by other instruments, we are really starting tobe able to put together a detailed picture of emissions."

Carbon storage and removal also has been investigated both inside and outside station. The ESA (European Space Agency) Photobioreactor study cultivated algae to examine whether microalgae could help close the carbon loop in future life support systems, and Kuwait's Experiment: E. coli C_5 studied the effect of microgravity on E. coli bacteria that were modified to consume carbon dioxide as food. Images taken by former space station payload HICO even helped develop an algorithm to detect harmful algal blooms, which

The suite of Earth-observing payloads attached to the Japanese Experiment Module is shown as the International Space Station orbits over the southern Pacific Ocean east of New Zealand in March 2018. Credit: NASA

The night lights of Tokyo, Japan, are pictured from the International Space Station as it orbited 420 kilometers (261 miles) above the island nation. Credit: NASA

can play a major role in the global carbon cycle.

With other devices such as SAGE-III tracking the recovery of ozone, NASA's ISS-LIS and ESA's ASIM monitoring lightning, and TSIS tracking the total energy flowing into Earth from the Sun, station experiments advance numerous climate records and models. Solar irradiance represents one of the longest climate data records derived from space-based observations. Researchers have been able to maintain continuity of that record with TSIS.

"Climate change presents what is perhaps humankind's greatest environmental challenge," says former TSIS principal investigator and University of Colorado Boulder professor Peter Pilewskie. "Monitoring the energy that flows into, within, and out of the system underpins our ability to understand how the climate system works, recognize that it is changing, and identify those mechanisms responsible for climate change."

The space station offers a standardized, capable platform to house Earth observation experiments such as TSIS. The size of a football field and equipped with numerous attachment points, plenty of data capacity, and a large power supply, the space station can host a wide variety of instruments simultaneously. The availability of these resources made the space station a great last-minute option for the TSIS team to quickly get its payload into orbit. After some delays, the team was facing potential failure of previous tracking instruments before TSIS could launch.

"It started to get pretty dire, because accuracy of the climate record is maintained at its highest possible level when the data record is continuous," says Pilewskie. "Because of space station, we were able to continue this record."

After researchers learn the basics of creating a payload for the space station, they can apply that knowledge to future station projects. Pilewskie is already working on his next experiment, CLARREO Pathfinder.

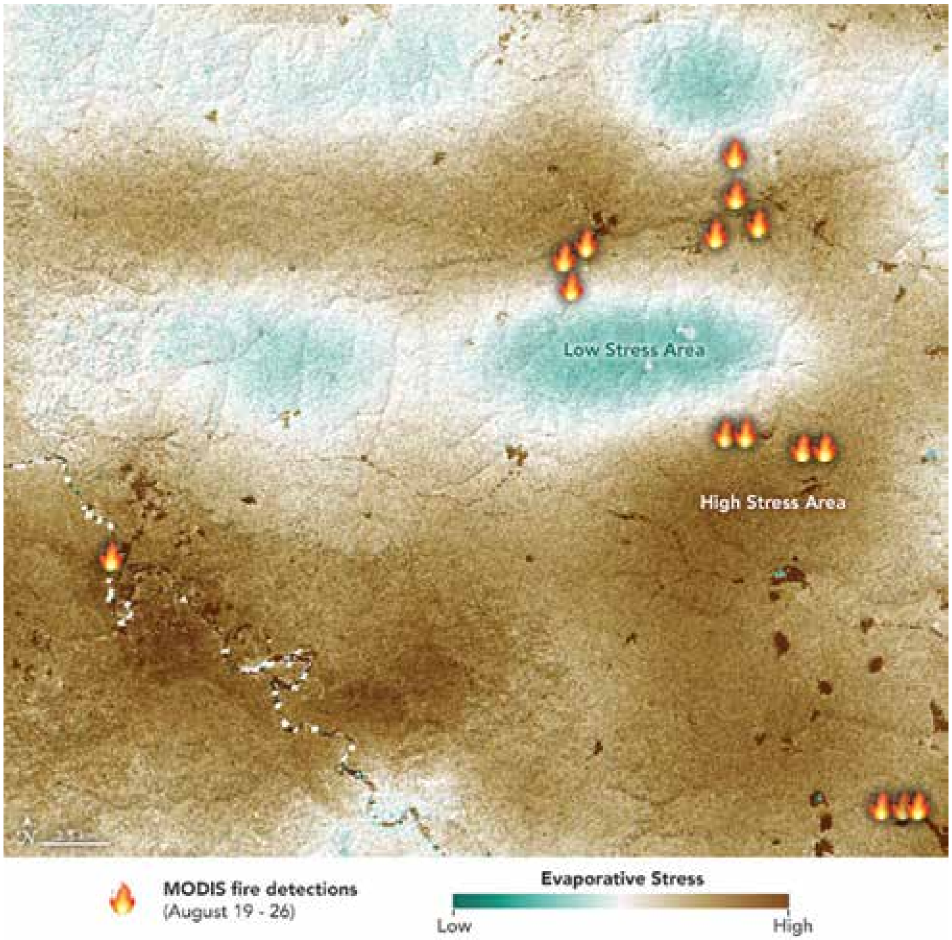
"The value that we gained from operating an instrument on station that needed to point very precisely cannot be understated," says Pilewskie. "We have to do the same thing with CLARREO Pathfinder, so we are using some of the same motors that we use to drive the TSIS instruments."

Scheduled to launch in the next few years, CLARREO plans to study Earth's climate by taking measurements of sunlight reflected by Earth and the Moon with five to ten times lower uncertainty than measurements from existing sensors.

Additionally, the Japan Aerospace Exploration Agency (JAXA)'s integrated Standard Imager for Microsatellites (iSIM), a high-resolution optical binocular telescope developed by Spanish company SATLANTIS, takes images of Earth at less than 1 meter (39 inches) of resolution.

It is not only sensors monitoring our planet from above. People do so as well.

The windows of the space station provide an opportunity for astronaut photography and manual collection of climate data. Astronauts have taken more than 4 million images of Earth



NASA's ECOSTRESS sensor measured the stress levels of plants when it passed over the Peruvian Amazon rainforest on Aug. 7, 2019. The map reveals that the fires were concentrated in areas of water-stressed plants (brown). The pattern points to how plant health can impact the spread of fires. Credits: NASA/JPL-Caltech/Earth Observatory

Preflight side view of the JAXA iSIM-IOD flight unit. Developed by SATLANTIS, iSIM is a new-generation, high-resolution optical payload binocular telescope for Earth observation. The design combines class-leading performance via the utilization of cutting-edge technologies, significantly reduced build times, and a new level of affordability. Credit: SATLANTIS

from space (over 3.5 million from the space station), contributing to one of the longest-running records of how Earth has changed over time. Crew Earth Observations currently support urban night lighting studies, glacier and volcano monitoring, and studies of atmospheric processes affected by volcanic eruptions. The ROSCOSMOS Hurricane-Visual study also contributes imagery that assists with Earth monitoring, providing an additional source of data. These images also support relief efforts for disasters such as hurricanes and wildfires.

Station even extends its climate science impact by deploying CubeSats into low-Earth orbit. These shoebox-sized devices contain technology demonstrations or test new types of climate science. Astronauts unload and prep them on station and then deploy the devices out of the space station airlock.

"That has been a great resource for small programs, especially universities or NASA centers trying to get some small projects going. CubeSats might be their first stepping-stone to larger things," says TSIS and NanoRacks-MinXSS principal investigator Tom Woods. "Space station offers a lot of opportunities to get these smaller things into space."

Climate CubeSats deployed from station include the following:

- The student-designed NanoRacks-MinXSS CubeSat targeted a better understanding of solar X-ray energy and how it affects the layers of Earth's upper atmosphere.
- JAXA's DIWATA-1 satellite provides remote sensing information to the Philippines by observing meteorological disasters such as typhoons and localized heavy rains.
- NASA's HARP CubeSat helps us better understand how clouds and aerosols impact weather, climate, and air quality.

As Earth's climate changes, the International Space Station will be watching from above, helping provide unique insights needed to keep our planet safe.

Russian cosmonaut Dmitry Kondratyev (left) and ESA (European Space Agency) astronaut Paolo Nespoli use still cameras to photograph the topography of points on Earth from windows in the cupola of the International Space Station. Credit: NASA

Observing Our Planet from Low-Earth Orbit

NASA astronaut Chris Cassidy uses a 400-mm lens on a digital still camera to photograph a target of opportunity on Earth some 250 miles below him and the International Space Station. Credit: NASA

The phrase “a picture is worth a thousand words” has never been truer than when it comes to the photographs and imagery produced by crew aboard the International Space Station. Orbiting around Earth every 90 minutes at an altitude of approximately 402 kilometers (250 miles), the station provides a spectacular vantage point to take pictures of our planet. From this setting, crew members aboard the space station have taken more than 3.5 million photographs of Earth. These photos have added to long-running image-capture programs reaching back to the 1960s for both the Russian and U.S. space programs. The State Space Corporation ROSCOSMOS (ROSCOSMOS) Uragan-Vizual (Hurricane-Visual) and Crew Earth Observations investigations task crews aboard the station with capturing photographs of significant features on Earth’s surface.

After completing scientific observation training provided by specialists, crew members use hand-held cameras to regularly take photographs of features such as volcanic eruptions, urban areas, bodies of water, and meteorological phenomena. The information gathered by crew photographs supports global-scale investigations related to the composition, health, and future of Earth.

Flooding in Colombia

The mighty Orinoco River serves as a boundary between the countries of Colombia and Venezuela. Four major rivers in Colombia's Oroniquia region drain into the Orinoco. Significant flooding in this region in early July 2020 affected more than 1,200 families and destroyed an estimated 1,600 hectares (almost 4,000 acres) of crops.

The Colombia Institute of Hydrology, Meteorology and Environmental Studies asked NASA's Earth Applied Sciences Disasters Program to help determine the extent and impacts of the flooding. The program's tools include Crew Earth Observations, consisting of photographs taken by astronauts on the space station. Later in the month, NASA astronaut Chris Cassidy was able to capture images of the flooding as the space station passed over Colombia. NASA's Earth Science and Remote Sensing Unit at Johnson Space Center matched the photos with locations on the ground, and the Disasters Program then sent them to Colombian authorities.

"The information was essential in supporting quick and remote analysis of flood zones," said Johan Naranjo, a Geographic Information System expert with Colombia's National Unit for Disaster Risk Management. Officials used the images to carry out an analysis of flooded areas over multiple days, which helped them identify those sites most critical for direct emergency response by national, departmental, and municipal authorities. The photograph helped fulfill the purpose of the International Disaster Charter, which states that it strives to provide Earth observation data to aid in rapid disaster response efforts.

Volcano Spotting

When NASA astronaut Jeff Williams looked out the space station window in 2006, he saw something unexpected: a volcanic eruption. What he did not realize is that he was the first person to witness this eruption of the Cleveland Volcano in Alaska. Cleveland Volcano, situated on the western half of Chuginadak Island, is one of the most active volcanos in the Aleutian Islands, which extend west-southwest from the Alaska mainland. His unique vantage point allowed him to be the first human to alert the Alaska Volcano Observatory that the volcano had produced a plume of ash. Shortly after the activity began, he took this photograph.

Gazing Through the Darkness

From their unique setting in low-Earth orbit, station crew members regularly generate nighttime imagery that captures twinkling light sources on the surface. This photo of the Iberian Peninsula taken by ESA (European Space Agency) astronaut Alexander Gerst and composite image taken by NASA astronaut Christina Koch as station traveled from Namibia toward the Red Sea show just how bright nighttime lights can be. This type of imagery can help researchers track light pollution and conduct studies of urbanization.

The View from the Cupola

The space station's cupola is a research module with seven viewing windows, making it a great location to take pictures of Earth. Gazing outside one of the cupola's side windows, NASA astronaut Andrew Morgan captured this image of the Caribbean Sea. The largest land mass featured in this photograph is Cuba, and to the right of it is the Bahamas. The Bahama Banks, submerged hills comprised of limestone and sediments formed from the biological processes of ancient and current sea life, can also be seen just below the surface of the blue waters. Numerous images like this make up NASA's Gateway to Astronaut Photography database that scientists can pull from for their studies.

NASA astronaut Leland Melvin prepares to use a still camera at a window in the Zvezda Service Module of the International Space Station to take pictures of the Earth. Credit: NASA

NASA astronaut Christina Koch takes photographs of Earth landmarks as the orbiting lab flies 417 kilometers (259 miles) above the Pacific Ocean off the coast of South America. Credit: NASA

ESA astronaut Alexander Gerst peers out the International Space Station's "window to the world," the seven-windowed cupola. Credit: NASA

Student Space Photos

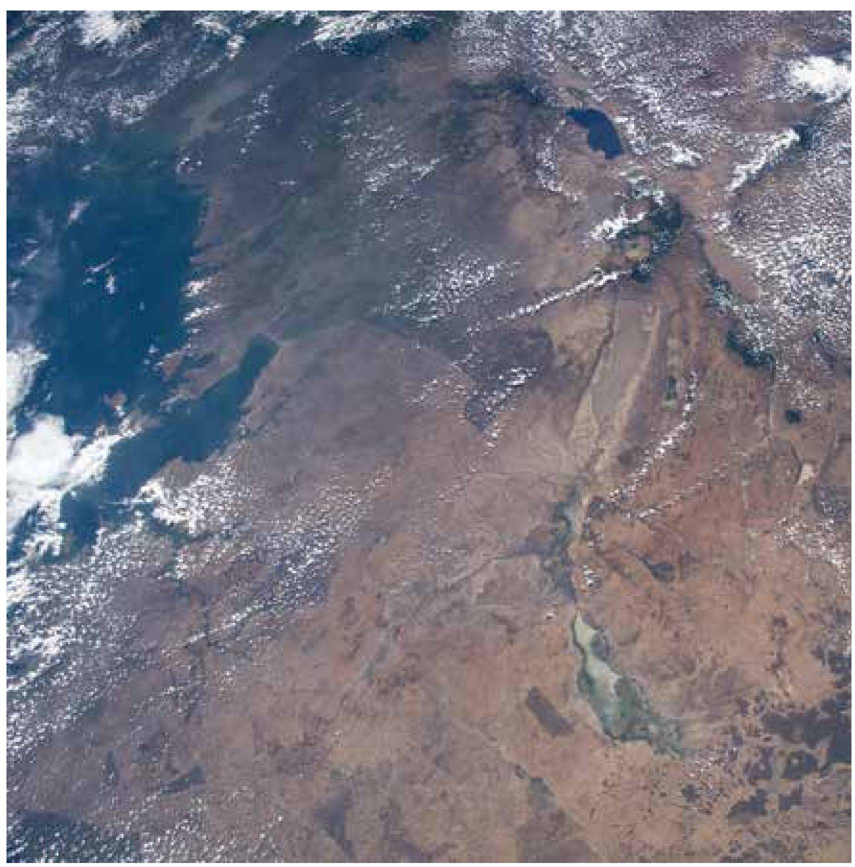
Can you spot the rivers in this photograph of the Arabian Desert's Deerat Valley? Near the southwestern edge of the Red Sea lies a collection of rivers that frequently vanish due to the severe dryness of the region. The darker surfaces are comprised of ancient Precambrian rocks that are more than 540 million years old, while the lighter expanse is a mixture of younger sediments forming sand dunes. In 2017, the Sally Ride EarthKAM captured this scene in which eroded sediments from the Precambrian rock exposures highlight the peaks of the silicate sand dunes.

The Sally Ride EarthKAM is an educational outreach program that has enabled more than 1 million students to participate in taking photographs from space by requesting images from a designated camera. "It is an elegantly elaborate, yet very practical program, that allows school children access to real time science on the space station," said Vice President of Education at the U.S. Space and Rocket Center, Dr. Kay Taylor.

A Higher-than-birds-eye View

The AMASS investigation is a collaborative effort between NASA, the Canadian Space Agency (CSA), and the Bondar Foundation. The AMASS investigation began in 2016 with a focus on photographing migratory locations of the whooping crane, highlighting along those routes habitat changes caused mainly by human activities. It expanded its breadth when CSA astronaut David Saint-Jacques boarded the space station in 2018. The project's expansion included surveying the migratory locations of six additional avian species. "One of the challenges of taking photos of Earth from the space station is that we are going pretty fast. You know, we are going around the world in about an hour in a half," Saint-Jacques says. "Chasing the right frame is a bit of an art because you only have one chance."

This image contributed to the AMASS investigation by photographing a significant habitat for lesser flamingos near Africa's Lake Victoria to the left and Lake Natron in the upper right.



A Swirling Storm

Cosmonaut Sergey Ryazansky photographed Hurricane Irma as the space station flew over the storm in 2017. Growing to a Category 5 storm, Hurricane Irma is among the strongest Atlantic hurricanes ever observed. Images like this can support disaster response on the ground. After receiving notification that a natural disaster is occurring or has occurred, scientists on the ground determine whether the crew will be able to see the affected area while orbiting overhead. If so, the crew captures and sends imagery back to Earth. The pictures are then georeferenced for use by hazard teams on the ground. Astronaut imagery has been useful for wildfire events, for example, showing responders where the smoke plume is going.

A Glimpse of the Milky Way Over the Pacific Ocean

In this 2015 image taken by NASA astronaut Kjell Lindgren aboard the space station, the scene is illuminated by multiple light sources. Countless stars within our galaxy, the Milky Way, stand out among the encroaching dust clouds. Orange, green, and red airglow layers can be seen, highlighting Earth's curvature. In the lower right of the foreground, a lightning flash illuminates a large cloud mass over the Pacific Ocean. With dense cloud cover over a majority of this scene, the light sources make for a stunning sight.

This photo taken from the International Space Station helped identify distinct land features on Tenerife Island in Spain’s Canary Islands. Artificial intelligence has assessed images like this to identify lava flows and volcano types in photographs captured worldwide. Credit: NASA

AI-Spy with My Little Eye

Spotting Topographic Changes from 250 Miles Above

Crew members aboard the International Space Station capture imagery during studies like Crew Earth Observations and Hurricane-Visual, pointing cameras at interesting features on our planet. Once a picture is taken, it often needs further processing to enhance its scientific usefulness. Historically, this step has been a manual task, but now researchers are assigning it to artificial intelligence (AI).

The Earth Science and Remote Sensing Unit at NASA’s Johnson Space Center in Houston, Texas, is using machine learning to sort through and identify photos taken from the orbital laboratory, making them more searchable and useful to scientists. The Gateway to Astronaut Photography of Earth service contains nearly 4 million astronaut-captured images. Using AI, researchers have categorized over 2 million photos of Earth’s geographic features, 250,000 images of auroras, 37,000 lightning photos, and 18,000 images of 64 different cities around the world.

While the technology to capture imagery of Earth from satellites has existed since the 1960s, use of AI in image processing is a recent development. After training the AI model on satellite imagery of Earth, NASA scientists began using it to process significant quantities of imagery at a rate far faster than any human cataloger.

“Crew Earth Observations serves as a longitudinal record of what the Earth looks like at specific times,” said data scientist Alex Stoken, who works on the team responsible for managing the operation. “For example, NASA has a 20-year photographic record of the Toshka Lakes in Egypt that can be studied to understand the changes to water levels in the lakes. With AI, we can identify more of these change areas and study them in greater detail.”

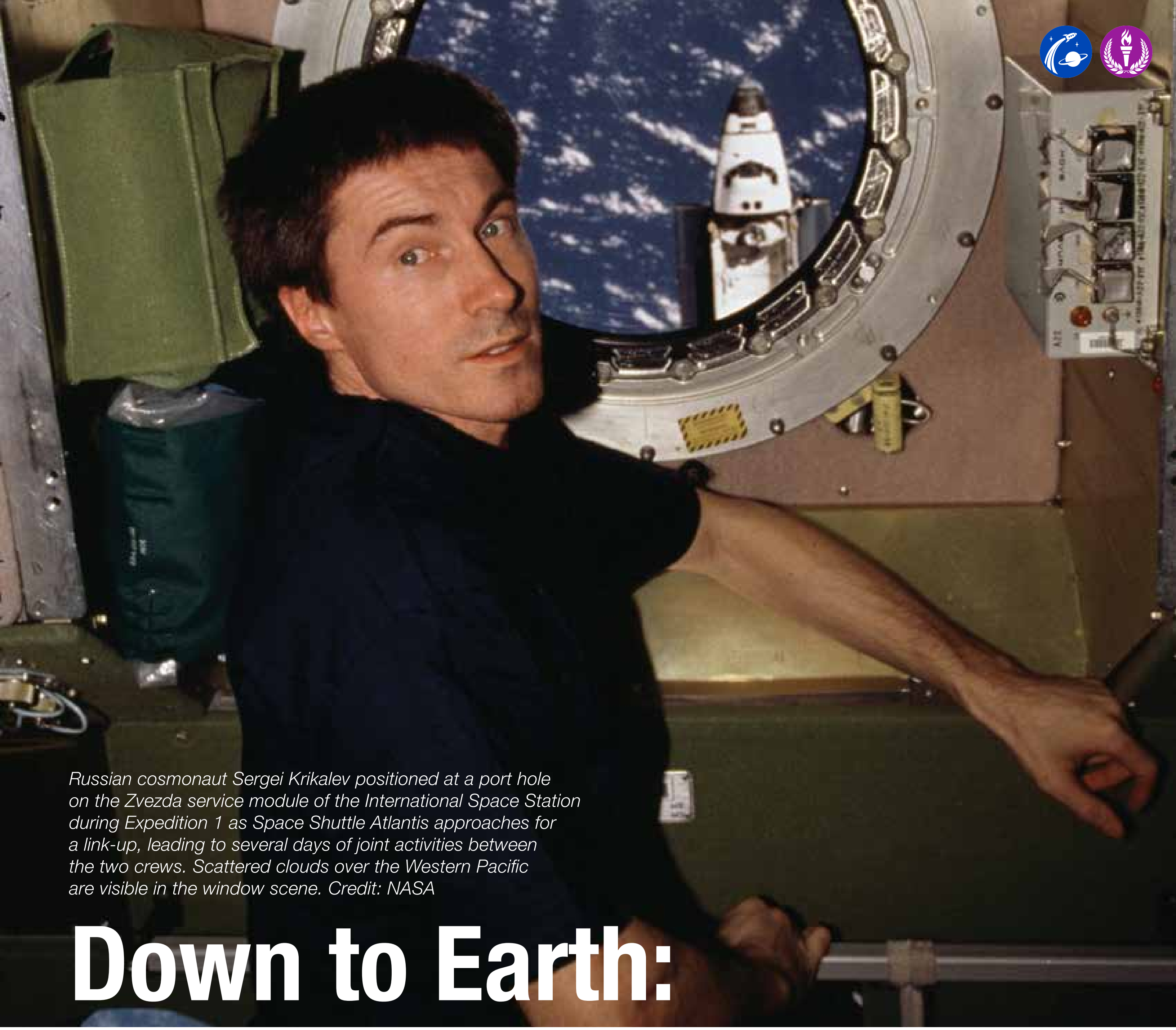
> "Analyzing modern astronaut imagery helps researchers to better understand Earth and its changing landscapes...

Scientists also request images of Earth sites that have comparable features to structures on other planets, such as impact craters. For example, Tenerife Island, the largest of the Canary Islands, has formations over 30 million years old that are reminiscent of features found on other planetary surfaces.

"When we use machine learning to identify mountainous photos or photos with large boulders, we are also searching for potential sites that are analogous to places on the Moon and Mars," said Stoken. "If we can better understand how those processes happened on Earth, maybe it will teach us something about other potential future space destinations."

Analyzing modern astronaut imagery helps researchers to better understand Earth and its changing landscapes and to refine and validate algorithms to support future exploration missions and aid planetary scientists in studying our solar system.

Mosaics created from astronaut imagery of the Toshka Lakes in Egypt. The top image, taken in 2002, and the bottom image, taken in 2015, show how these bodies of water have changed over time. Credit: NASA



Russian cosmonaut Sergei Krikalev positioned at a port hole on the Zvezda service module of the International Space Station during Expedition 1 as Space Shuttle Atlantis approaches for a link-up, leading to several days of joint activities between the two crews. Scattered clouds over the Western Pacific are visible in the window scene. Credit: NASA

Down to Earth: Q and A with Cosmonaut Sergei Krikalev

No matter how many pictures of Earth you see, nothing can match gazing out the windows of the International Space Station at our planet rotating below. For the few hundred people who have had that privilege, it can be life changing.

To come as close as possible to experiencing this perspective, view Earth through the eyes of Russian cosmonaut Sergei Krikalev, who ranks third to cosmonauts Gennady Padalka and Yuri Malenchenko for time spent in space, logging over 800 days aboard the International Space Station, Mir space station, Soyuz spacecraft, and the space shuttle. He kicked off more than 20 years of continuous human habitation aboard station in November 2000 as one of three members of Expedition 1. Krikalev shared his unique perspective on the power of collaboration in space and looking down on Earth.

Backdropped against heavy cloud cover, the International Space Station is photographed with a 35-mm camera by one of the astronauts onboard Space Shuttle Atlantis in February 2001. Credit: NASA

What was it like seeing the Earth from space for the first time?

I was amazed to see the horizon. Before that, when on the globe, I flew very high on different airplanes and still saw a flat horizon. But from orbit, you can already see a curvature of Earth. The second surprise was to see with your own eyes that we have a pretty thin layer of atmosphere protecting us.

> “When you see some unusual structure of clouds, you take a picture, knowing that people are studying some effects in the atmosphere. Then we have a very interesting discussion with scientists to explain what we see.

How would you describe the colors of the planet below?

I remember discussing with scientists before the flight that everyone reports seeing bright colors, but from a scientific point of view, when you look down, you have a blue filter. This blue filter makes all colors actually not so distinct. The same way, when we look up at the sky and we see blue sky, we actually see a thick layer of atmosphere between us and Earth’s surface.
So really, green is not so green. It is more like bluish green. Blue is bluer because we have more blue from the atmosphere. Where we have really bright colors is on the horizon, especially during sunrise and sunset.

How did the pictures you took contribute to science?

We actually not only had specific directions from scientists, but they also educated us generally on what they may be interested in. So if I see something, even if I do not have direct guidance from scientists, I know that, for example, this bloom of water from a river into the ocean and see how spreads different colors in the ocean can be interesting. And it can be interesting, actually, for several scientists. For oceanographers, for people who study living creatures in fresh water and salt water, to know how this water spreads. And sometimes you can really see what is happening when two different waters mix.
When you see some unusual structure of clouds, you take a picture, knowing that people are studying some effects in the atmosphere. Then we have a very interesting discussion with scientists to explain what we see.

> “When you see a forest fire, you see that smoke is going sometimes for hundreds of kilometers. They cross all borders. There is no wall on this border. If you have disaster on one side, it can easily spread on another side.

Did you have any big takeaways from your first time in orbit?

I remember from my first flight, when you look down, it is a little more difficult to find things on the surface. When you do it on the map, you have borders and start to use borders as a landmark. But in space, you have no borders. You have only the natural rivers, mountains, beaches, forests, or something like that. You start to understand that in many cases, our separation on Earth is more artificial. We are living on the same surface. When you see a forest fire, you see that smoke is going sometimes for hundreds of kilometers. They cross all borders. There is no wall on this border. If you have disaster on one side, it can easily spread on another side. If you have flooding, it floods an area not looking at the border between different regions or different countries. You start to see that we are more united.

This feeling of being united, how do you think it can be brought back down to Earth?

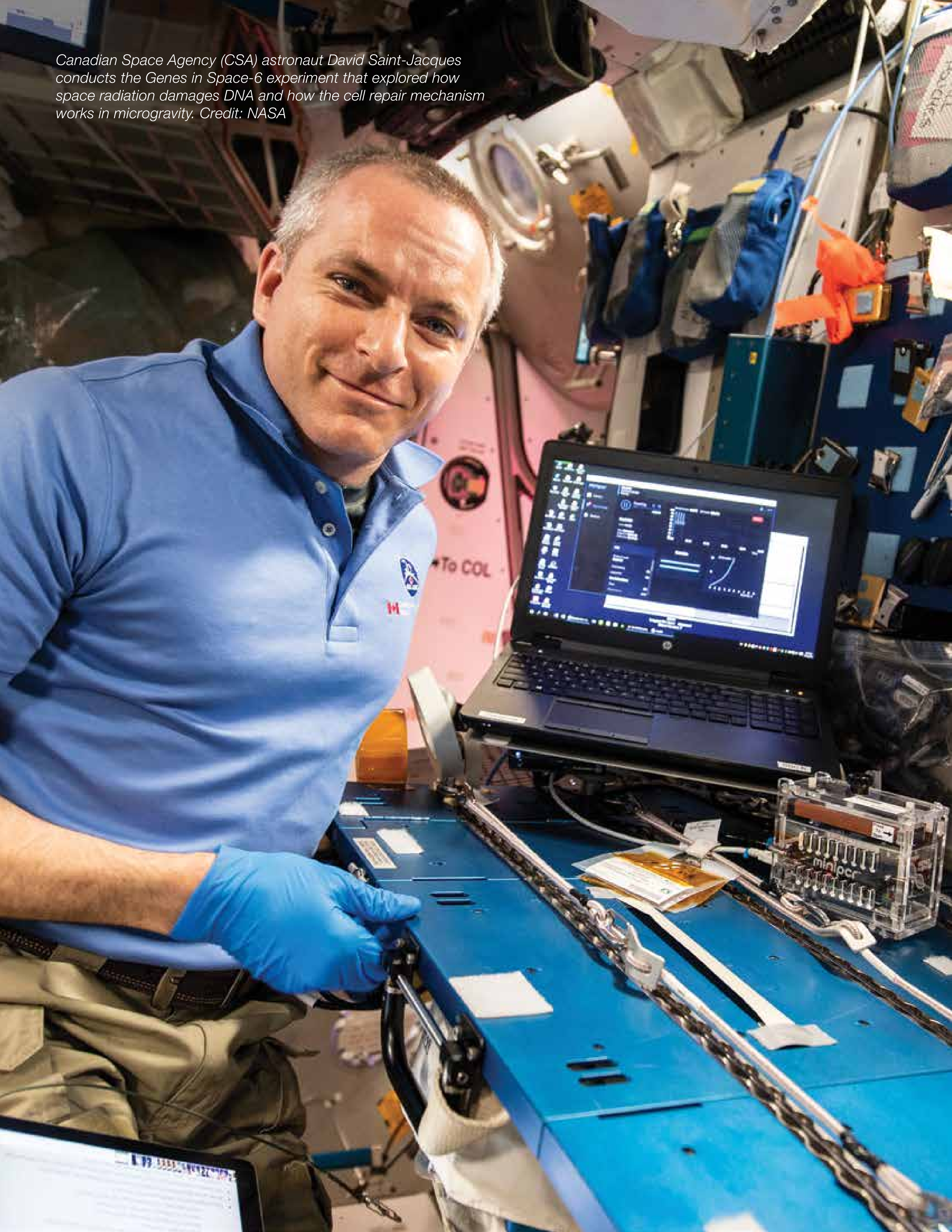
I think what we do in space together is a good example of how people need to live on the ground. I know that people sometimes start to argue with no good reason; but especially when you are in a harsh environment, you rely on each other and try to help each other. That is how we live in space, and that probably can be a good example for people on the ground. We try to keep this area protected and keep this good example to politicians and maybe other people in my country and your country, showing that is really how we need to live.

The Expedition 11 crew aboard the space station, including cosmonaut Sergei Krikalev, flexes the Canadarm2 while flying approximately 362 kilometers (225 miles) above Cape Horn. Credit: NASA

NASA astronaut Kate Rubins conducts microbiology research in the Japanese Experiment Module (JEM) of the space station. The experiment studied the relationship between humans and microbes in space habitation environments. Credit: NASA

Microbiology in **Microgravity**

> *It's a world-class laboratory and it's an absolutely packed one. I think it's like taking an entire university campus, a world-class university, and shrinking it down to the size of the space station.*
>
> *-NASA astronaut Kate Rubins*



Canadian Space Agency (CSA) astronaut David Saint-Jacques conducts the Genes in Space-6 experiment that explored how space radiation damages DNA and how the cell repair mechanism works in microgravity. Credit: NASA

Our Relationship to Microbes on the International Space Station

Anything launched to space is meticulously tested, monitored, and often sanitized. However, our control over spacecraft and the items aboard is not total, especially at the microscopic level. Microbial hitchhikers still have the capability to catch a ride to space, with either the cargo or the crew.

While people literally could not live without these tiny organisms, many of which are benign or beneficial, there is still a possibility that the assortment of bacterial hitchhikers could include disease-causing pathogens that might make the crew sick. That is why scientists use the International Space Station as a testing ground to study how to keep astronauts safe and healthy on long-duration missions. These studies also benefit humans on Earth by providing a better understanding of how microbes behave in a sanitized, isolated, and confined environment.

This work is also forming a new area of scientific research. Many microbes can be stressed by the conditions of space, and some respond with genes encoding resistance to antimicrobial agents. It is therefore important to understand what types of space-residing microbes are present in the environment and whether they can become impervious to sanitation techniques.

"The goal is to enable near-real-time microbial diagnostics of the space station environment," said Sarah Wallace, a microbiologist in the Biomedical Research and Environmental Sciences division at NASA's Johnson Space Center in Houston. "We are looking at what is in the air, on surfaces, and in the water that the crew is surrounded by all day, every day."

Known, worrisome bacteria can be identified by their unique biological blueprint, contained within molecules of deoxyribonucleic acid (DNA). DNA is made up of four base molecules that link together to encode instructions for cell growth and behavior. Identifying the order of the bases using the process of DNA sequencing clues researchers in to the identity of the organisms and how they might behave.

A researcher at Johnson Space Center performs DNA and RNA sequencing on microbes as part of the Biomolecule Extraction and Sequencing Technology (BEST) experiment. The same sequencing procedure was performed in orbit aboard the International Space Station, and the results were compared to those on the ground. This capability provides better insight into the effects of the spaceflight environment on microbial life. Credit: Johnson Space Center

As the studies continue taking measurements, the data can expose patterns that exist in microbial composition on the space station. "It is kind of like taking a census," said David J. Smith, acting chief of the Space Biosciences Division at NASA's Ames Research Center in California's

Members of the Biomolecule Sequencer team pose together with their experiment. Credits: NASA/Bill Stafford

Silicon Valley. “The demographics data collected can be used years down the road for planning decisions about how we coexist with microbes in spacecraft.”

However, taking the census can be complex. The equipment required for DNA sequencing has historically been expensive and time intensive and has required specialized expertise to operate, limiting its use in space. For example, a series of NASA microbial tracking experiments and the 3D Microbial Monitoring study had to rely on astronauts collecting hundreds of samples by wiping down selected surfaces with swabs, packing the samples in plastic bags, and sending them back to Earth for identification with DNA sequencing facilities.

Sending samples from the orbiting lab back to Earth is complicated and adds significant time between the initial sampling and identifying the microbes present. The quicker we can identify unknown microbes on the International Space Station, the more prepared the crew will be to respond.

The key is finding a way to do complex microbial ecology surveys in space.

Microgravity and the restrictions on size and chemicals that can be safely used in the enclosed environment of the space station add to the challenge of designing a DNA experiment for space.

“We broke it apart at every angle and looked at how we can use the least amount of and safest tools and substances and get the best science,” said Wallace. “That is where we go outside of the box and come up with a different solution.”

Thanks to the work of Wallace and her team, sample return could soon be a thing of the past for microbiology studies.

In 2016, NASA astronaut Kate Rubins successfully conducted the first DNA sequencing in space, while researchers on the ground performed the same experiment, opening the door to molecular biology research in spaceflight conditions. The team used a MinION (pronounced “min ion”) sequencing platform, a device no bigger than a cell phone, to read the

NASA astronaut Joe Acaba with one of the Microbial Air Samplers, devices that monitor microbes in the air of the space station. Credit: NASA

NASA astronaut Kate Rubins prepares for a run of the Biomolecule Sequencer experiment. It seeks to demonstrate, for the first time, that DNA sequencing is feasible in an orbiting spacecraft. A space-based DNA sequencer could identify microbes, diagnose diseases, help researchers understand crew member health, and has the potential to help detect DNA-based life elsewhere in the solar system. Credit: NASA nucleic acid bases in samples sent to the station for study. This technology can enable scientists to quickly identify pathogens on the space station or on future exploration missions, and even potentially identify life on other planets in the solar system if it shares a common biochemistry with life as we know it on Earth.

"Our first sequencing demonstration in space was a big deal because the work was done from concept to flight in less than a year. Traditionally, it takes a much longer time to get a new instrument on station," said Smith. "We showed it is possible to be nimble in our science as we go beyond low-Earth orbit with future experiments."

The initial work of DNA sequencing opened the door to using other molecular biology methods in space. "Having an entire molecular laboratory in space is just going to explode what we can do there," said Wallace.

And explode it has. Astronauts used a genome editing technique called CRISPR (Clustered Regularly Interspaced Short Palindromic Repeats) for the first time in space, significantly expanding the space station's molecular biology toolkit once again by enabling studies of DNA repair. Numerous students have sent DNA research to space through the Genes in Space program. Scientists have even used MinION to fully identify unknown microbes on the orbiting laboratory without returning samples to Earth. The ability to identify microbes in space could aid in the diagnosis and treatment of astronaut ailments in real time. NASA astronaut Ricky Arnold even deployed the Biomolecule Sequencer with a swab method that did not require growing the bacteria prior to sequencing. With this direct "swab to sequencer" method, the

"The initial work of DNA sequencing opened the door to using other molecular biology methods in space.

NASA astronaut Ricky Arnold swabbed surfaces in the International Space Station to collect microbe samples. He then processed the microbial DNA using the Biomolecule Sequencer, a device that enables DNA sequencing in microgravity, to identify microbes able to survive in microgravity. Credit: NASA

DNA Sequencing in Space Timeline

February 1953 - Francis Crick, James Watson, and Rosalind Franklin discover the double helix structure that makes up DNA.

December 1977 - Frederick Sanger develops the first DNA sequencing method to read the genome of a virus.

July 1995 - First full bacterial genome sequenced (H. influenzae) with shotgun sequencing, which breaks the genome into small fragments that are sequenced individually using the chain termination method, then reassembled.

February 2012 - Oxford Nanopore Technologies debuts the first nanopore sequencer that uses next-generation sequencing (NGS) with the MinION.

April 2016 - As a part of the NASA WetLab-2 study, NASA astronaut Jeff Williams performs the first RNA isolation in space from E.coli and collects data on the RNA expression levels in the microbe.

April 2016 - DNA is amplified for the first time aboard station by ESA (European Space Agency) astronaut Tim Peake using the first PCR machine sent to station by company miniPCR.

August 2016- NASA astronaut Kate Rubin sequences DNA in space for the first time.

August 2017 - NASA astronaut Peggy Whitson combines the miniPCR and MinION, sequencing and identifying the first unknown microbe from the station.

August 2018 - NASA astronaut Ricky Arnold demonstrates Biomolecule Extraction and Sequencing Technology (BEST) by using culture-independent methods to sequence DNA on station for the first time with a "swab to sequencer" method. This process speeds up the rate of sequencing, no longer requiring the time and resources needed to grow the bacteria prior to analysis.

May 2019 - NASA astronaut Christina Koch performs the first CRISPR-Cas9 gene editing on station, using yeast to mimic the effects of space radiation on human DNA.

February 2021 - The crew performed more than 800 microbial sample collections throughout station for the 3DMM experiment. Scientists used DNA sequencing and other analyses to construct the first comprehensive 3D map of bacteria and bacterial products throughout the station.

> While optimized microbiology procedures will help enable deep space exploration, developing an autonomous molecular laboratory is expected to benefit humanity on Earth as well.

process becomes faster and simpler for crew members to identify microbes onboard the station. This method is now being evaluated to replace culture-based microbial monitoring that is currently conducted aboard the space station.

While optimized microbiology procedures will help enable deep space exploration, developing an autonomous molecular laboratory is expected to benefit humanity on Earth as well. This could be especially true for remote communities and hospitals without a lot of technology or funding.

"The ability to generate near-real-time molecular microbial data could provide a huge benefit toward understanding and responding to the antimicrobial resistance crisis and in resource-limited environments," said Wallace. "It is great to see the parallels between our work and the work by other researchers that are implementing these tools in other diverse places. If you can do these types of investigations on the ocean floor, on the space station, or on a table in a remote village, you can do them anywhere."

Designing simple procedures that can be performed by crew members who may not be microbiologists and by workers anywhere who may not have genetics expertise broadens the capacity for disease testing in underdeveloped countries or remote settings on Earth.

The NASA research team has gone on to collaborate with the Centers for Disease Control, looking into how streamlined procedures developed for the space station can be implemented to determine the cleanliness of hospital rooms. Using these microbial tracking methods in hospitals could provide a much faster turnaround time, even when implemented by untrained individuals. This capability might give hospitals the tools to detect microbes that may be resistant to antibiotics that could be present even after cleaning.

"Surprises are embedded in basic research and exploration," said Smith. "It could be establishing a more efficient workflow for microbial identification, or a useful pattern revealed in space that would otherwise be hidden on Earth. We never fully know what we are going to discover in spaceflight and the potential benefits to humanity – and that is why it is worth doing."

A view at the cupola window of sample collection tubes containing swab samples of microbes for the 3DMM (Three-dimensional Microbial Monitoring of ISS Environment) investigation. The study analyzed and sequenced the DNA from bacteria swabbed from station surfaces to understand how microbes respond at a molecular level to specific stress conditions, including altered gravity and atmospheric composition. Credit: NASA

Preflight fluorescence microscopy image of microbial biofilm, Sphingomonas desiccabilis, *growing on a slide of basalt rock as part of the Biorock experiment. Organisms are stained with a DNA binding dye. Image Courtesy of ESA*

Harnessing the Power of Microbes for Mining

From the creation of traditional tools like pickaxes and hammers to modern miniaturized electronics, civilization has always been dependent on mining, or extracting, metals from the Earth. Conventional mining methods relied on heavy machinery, fire, and human labor. However, scientists have learned to harness the natural power of microbes to help. This process, called biomining, is used on Earth as a more environmentally friendly and cost-efficient way of obtaining these necessary metals. The same process could make it possible to extract valuable elements from asteroids and allow astronauts to biomine materials they need on missions to the Moon and Mars.

"Chemical methods of remediation can be very damaging, whereas bioremediation and bioleaching is environmentally friendly, and produces fewer toxins," said Charles Cockell, Biorock principal investigator and professor at the UK Centre for Astrobiology at the University of Edinburgh. "It is low energy demand: you give the microbes some food, and they go about their business of mining."

While biomining has been used on Earth to address problems of pollution such as acid mine drainage, metal extraction in space may be more complicated, as microgravity could alter basic physical properties such as convection and liquid mixing, and potentially could change how microbes attach to surfaces or form the biofilms necessary for the extraction process. In 2019, the ESA (European Space Agency) Biorock investigation conducted onboard the space station demonstrated that microbes can extract elements from basalt, a common rock on the Moon and Mars. A follow-on ESA investigation, BioAsteroid, took it a step further and tested biomining on actual asteroid material. The team showed that not only is it possible for microbes to mine elements in space, but some microbes may even perform their task better under microgravity conditions. According to Cockell, this shows that it may be possible to perform biomining in space, including collecting rare elements from asteroids. The next step involves biomining in space on a larger scale

"Right now, the bioreactors are very small. When we are using these bioreactors on a larger industrial scale, what would the effectiveness be on the surface of an asteroid?" said Cockell. "These results will help us better understand the mechanisms behind biomining and develop useful technology for Earth." .

ESA astronaut Luca Parmitano installs the Biorock experiment KUBIK reactor in the space station's Columbus module. The Biorock investigation is one in a series of experiments to gain insight into the physical interactions of liquid, rocks, and microorganisms under microgravity conditions for novel acquisition of materials in space. Credit: NASA

ESA (European Space Agency) astronaut and Expedition 66 Flight Engineer Matthias Maurer shows off the Touch Array used for the Touching Surfaces experiment. The microbiology study investigates a suitable design for antimicrobial surfaces for future human space missions and space habitats, including a variety of applications on Earth. Credit: NASA

Using Microgravity to Combat **COVID-19**

Through isolation, astronauts are well protected from infection while aboard the International Space Station. However, COVID-19 still affected station research activities. In addition to conducting studies aimed at ensuring the safety of the crew, researchers used the microgravity lab to contribute to the fight against the virus.

One experiment launched to the space station in December 2020 examined the efficiency of remdesivir, an intravenous antiviral drug currently approved by the Food and Drug Administration (FDA) for the treatment of COVID-19 in hospitalized patients. Using a commercially owned and operated research facility, Europe's International Commercial Experiment Cubes (ICE Cubes), researchers from ESA (European Space Agency) tested the drug's behavior in microgravity with the goal of increasing its efficiency. Scientists studied the physical and chemical behaviors of the drug and how it interacts with a delivery substance, cyclodextrin, that makes remdesivir soluble in water. Soluble drugs can be dissolved into a solution and administered via IV and, once administered, move more easily through the patient's bloodstream.

Studying the interactions between remdesivir and cyclodextrin in microgravity could allow researchers to enhance the ratio of the drug to cyclodextrin. Decreasing the amount of cyclodextrin in the IV bag reduces the risk to coronavirus-infected patients with pre-existing kidney problems.

Scientists leading another experiment already scheduled to be conducted aboard the station as the COVID-19 pandemic began expanded their analysis to contribute to COVID-19 research. Antimicrobial Coatings studied how effectively certain antimicrobial coatings could limit the growth and spread of pathogenic microbes on frequently touched surfaces. The study tested the coating on several materials representing high-touch surfaces in aircraft and spacecraft, such as tray tables, seat fabric, and belt buckles.

During a 6-month period, crew members touched the samples every few days to encourage microbial growth. At the end of the experiment, the samples returned to a lab on Earth for analysis. This research was originally intended for use on space missions, but as the COVID-19 virus spread, scientists adapted the research to also test effectiveness in preventing the spread of viruses on surfaces as well.

Additionally, several companies have demonstrated that their air-quality technologies developed for the space station could reduce the spread of COVID-19. A technology tested for detecting contaminants on the space station went on to be included in an air sensor used on Earth to generate a virus propagation risk index in shared spaces, letting people know to reduce crowding or take other steps to limit risk.

Airgloss' air quality sensors work in conjunction with a thermostat to regulate ventilation and manage indoor air, sending alerts and reports. During the pandemic, the company learned how the sensors could calculate the risk of COVID-19 spread in certain spaces. Credit: Airgloss

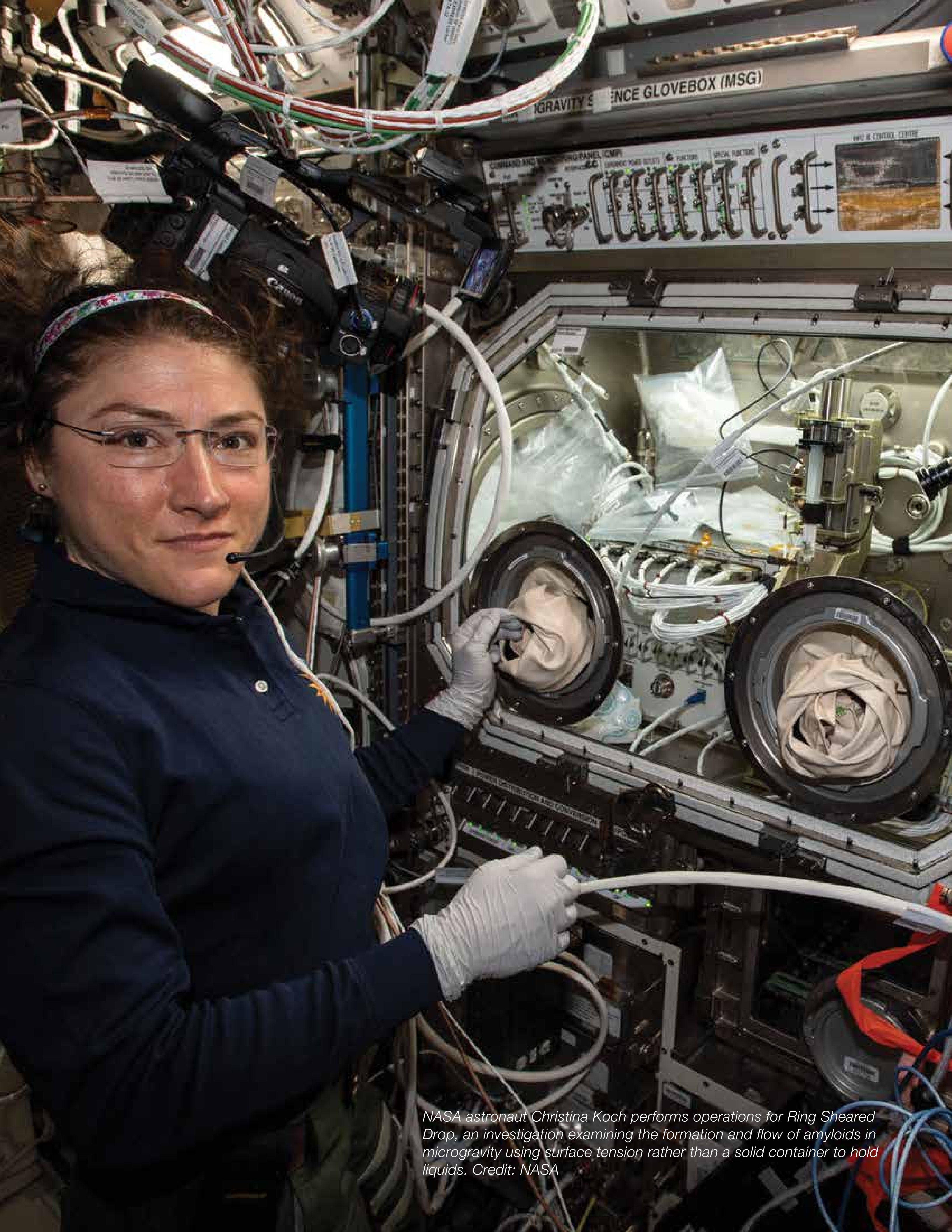
The ESA ICE Cubes facility in the Columbus European Physiology Module where an experiment to improve the ratio of the antiviral drug remdesivir to a solubility agent could make it safer to administer to patients with pre-existing health issues such as kidney failure. Credit: NASA

Advancing Human Health

JAXA astronaut Akihiko Hoshide working on Real-time Protein Crystal Growth Microscopy Plate S/N C1 Row B, Day 7. Credit: NASA

"On board the International Space Station, we help with development of medicine. Without gravity, we get larger chunks of pure protein crystals, which could accelerate the analysis and development process for new medicine.

-JAXA astronaut Akihiko Hoshide



NASA astronaut Christina Koch performs operations for Ring Sheared Drop, an investigation examining the formation and flow of amyloids in microgravity using surface tension rather than a solid container to hold liquids. Credit: NASA

Space Station Leads to Breakthroughs in Human Health on Earth

As a cup of water sits on the corner of a desk, gravity pulls the liquid down. The walls of the cup push back, keeping the water in place. Those of us living on Earth hardly give a second thought to these forces, but for scientists working to unravel the mysteries of disease, the effects of gravity and the forces of containers on scientific samples may alter experimental results and hinder breakthrough discoveries.

NASA's Ring Sheared Drop experiment is helping overcome this hurdle. Researchers developed a device for use aboard the International Space Station that uses surface tension to contain the liquid rather than a solid container, something possible only in microgravity.

The aim of this research was to create protein aggregations called amyloid fibrils. These fibrils form a waxy plaque in the brain believed to destroy neurons, a possible cause of Alzheimer's disease. The study confirmed that the surface tension concept worked. This ability to process materials without containers in microgravity benefits other experiments, including those that grow protein crystals and microorganisms as well as studies of pharmaceutical manufacturing.

Ring Sheared Drop is one of many investigations on the space station that have examined the causes, progression, and treatment of a variety of diseases, and explored basic mechanisms of human physiology.

A new way to look at Alzheimer's

Researchers from around the world use the space station to address complex human health problems on Earth. Studies examining the formation of amyloids started after evidence suggested similarities between their formation and protein crystallization, a process already extensively studied in space.

In preparation for the station experiment, Ring Sheared Drop hardware also was tested on parabolic flights in a collaboration between the Rensselaer Polytechnic Institute in New York and researchers from NASA's Marshall Space Flight Center in Huntsville. These experiments tested and verified novel concepts to accommodate fluid attachment to the metal rings for the space station experiment. In addition, the team plans to use results from these tests in designing additional investigations on the space station. In a ground-based lab, similar results were achieved using a drop of silicone oil in water (rather than a drop of liquid surrounded by air) to account for the effects of gravity. This approach does, however, introduce instabilities probably not present in microgravity.

"So, we were able to simulate microgravity in one respect and make a ring sheared drop at the same scale in the lab as in space," says principal investigator Amir Hirsa of the Rensselaer Polytechnic Institute. "But the protein solution we sent to

ESA astronaut Alexander Gerst exhales into an analyzer for the Airway Monitoring experiment, which studies airway inflammation in crew members. The investigation could help keep crews safe on long-term missions to the Moon, Mars, and beyond, and improve treatments for patients on Earth with asthma or other airway inflammatory diseases. Credit: NASA space is many orders of magnitude more viscous. So, you can match some but not all aspects of the space experiment. No surprise, heaven and Earth are not interchangeable: there is just no replacement for microgravity."

The Ring Sheared Drop device pins a drop of liquid between two rings and rotates one while keeping the other stationary to create shear flow, or a difference in velocity between adjacent liquid layers. Previous research shows that this shear flow plays a significant role in the early stages of amyloid formation. Creating the phenomenon is, therefore, an essential feature of the device, Hirsa explains. Other researchers already are using the method to examine actual transport of amyloid plaque in the brain, and it could ultimately benefit development of pharmaceuticals. "Our study may inform drug development, looking at how plaque can be transported out, and whether its transport causes more harm than good."

Hirsa notes that drugs for removing amyloid plaque from the brain have already been developed. "The idea of transport or flow of amyloid fibrils from a diseased brain is not a pipe dream, it is a focus of pharmaceutical research," he says. "Our work is one brick in a very large wall."

The Japan Aerospace Exploration Agency (JAXA) Amyloid study and the Amyloid Aggregation study, a collaboration between the Italian Space Agency (ASI) and ESA (European Space Agency), also analyzed amyloid fibrils formed in microgravity. Amyloid results published in 2020 reveal that fibrils form distinct structures and grow more slowly in microgravity, making the space station an ideal environment for detailed analysis of the mechanisms of how they form. Such analysis also could contribute to the development of new pharmaceuticals aimed at inhibiting amyloid fibril formation.

> "Research aimed at protecting the lungs and airways of astronauts is helping people with asthma and other breathing issues on Earth.

NASA astronaut Serena Auñón-Chancellor works on AngieX Cancer Therapy, a study testing a safer, more effective treatment that targets tumor cells and blood vessels. Credit: NASA

Breathing easier in space and on Earth

Research aimed at protecting the lungs and airways of astronauts is helping people with asthma and other breathing issues on Earth. For ESA's Airway Monitoring study, which builds on results from earlier NOA-1 and NOA-2 experiments conducted aboard the International Space Station, researchers at Sweden's Karolinska Institute collaborated with medical technologists and developed an instrument that measures exhaled air for nitric oxide. Clinics and hospitals already use the device as a quick, low-cost tool to help diagnose inflamed lungs and asthma, and testing the technique in space adds data for improving its use on Earth.

Astronauts breathed into the device in the reduced pressure of an airlock to simulate conditions in future habitats on the Moon or Mars. Lead investigator Lars Karlsson of Sweden's Karolinska Institute hopes that the experiment opens new fields of research in reduced pressure in space. Exhaled nitric oxide measurements also could be used to identify the most effective molecules for use in drugs to treat inflamed airways and lungs.

"One group of experiments that I enjoy most are those where we investigate our own human systems to help people with illnesses on Earth," says ESA astronaut Alex Gerst, who participated in the Airway Monitoring investigation. "It's another example of how we need to fly to space to help people down here."

Toward better cancer treatments

Cancer is a leading cause of death in the United States, accounting for hundreds of thousands of deaths each year. The International Space Station National Laboratory is advancing cancer research through studies that cultivate stem cells for possible therapeutic applications, crystallize proteins for improved drug discovery and delivery, and test therapies to find those that work better or have fewer side effects. Other projects seek to improve 3D cell culturing for more accurate drug testing that could reduce the failure rate of current drug discovery efforts.

Angiex, Inc. of Cambridge, Massachusetts, developed a treatment targeting the blood supply of tumor cells, which kills cancer cells by depriving them of oxygen and nutrients. The company's AngieX Cancer Therapy investigation took advantage of the space station's microgravity environment to culture endothelial cells, which line the walls of blood vessels, to see whether they might provide a valid model to help develop safer and more cost-effective cancer treatments.

"When scientists try to grow endothelial cells on the ground, they don't live for very long. One of the things we tested on orbit is whether the cells grow better in space," says NASA astronaut Serena Auñón-Chancellor. "Endothelial cells help provide blood supply, and tumors need blood supply to get bigger. If we can stop that tumor blood supply from growing, then we can help beat that cancer. All of us have had someone affected by cancer, whether a family member or friend, and we're always thinking of how we can fight it. One way is if we can grow these cells on orbit and use them to test new drugs that can prevent that blood supply from growing."

AngieX is only one of many investigations on the space station seeking better treatments for cancer.

Endothelial Cells, an ESA experiment that examined how cultured endothelial cells react to spaceflight, made modifications to the culturing hardware that can be put to use by these types of biomedical experiments in space.

Insight into the immune system

Astronauts experience impaired immune function in space. Impaired immune response also happens with aging on Earth. Space offers a unique advantage to studying this aging-related immune suppression since conditions that normally develop over decades happen quickly there. A growing body of research takes advantage of this fact.

ESA's Leukin-2 experiment demonstrated that microgravity has a fundamental effect on activation of T-cells, which are involved in turning on and off the immune system. Control samples also flew to the space station and were cultured in a centrifuge to simulate normal gravity to eliminate the effects of factors such as the stress of launch and increased radiation exposure in space.

"We were able to look specifically at what microgravity is doing to the cells," says Tammy T. Chang, a researcher at the University of California, San Francisco, and an author on several papers related to Leukin-2. "This study added an important piece of information to immune dysregulation seen in astronauts, that the cells themselves are sensitive to the presence or absence of gravity on a molecular level."

The same mechanisms may be behind immune dysregulation on Earth. "Researchers may be able to use microgravity to enhance self-assembly of complex tissues to study various human diseases," Chang says. Ultimately, this type of research could lead to drugs that turn up the immune response for immunosuppressed patients or turn it down to treat autoimmune or inflammatory disease.

Another ESA investigation, Immuno, also observed T-cell changes in space. Increased understanding of how stress affects the immune system could help people on Earth as well as support development of drugs to counter immune system changes for long-duration spaceflight.

Protecting muscles and bones

The ISS National Lab sponsored Mighty Mice in Space investigation showed that blocking a specific molecular signaling pathway involved in maintaining muscle and bone protected astronauts against bone and muscle loss in microgravity, and even stimulated growth. Results suggest that this strategy could prevent and treat such loss in people on Earth as well.

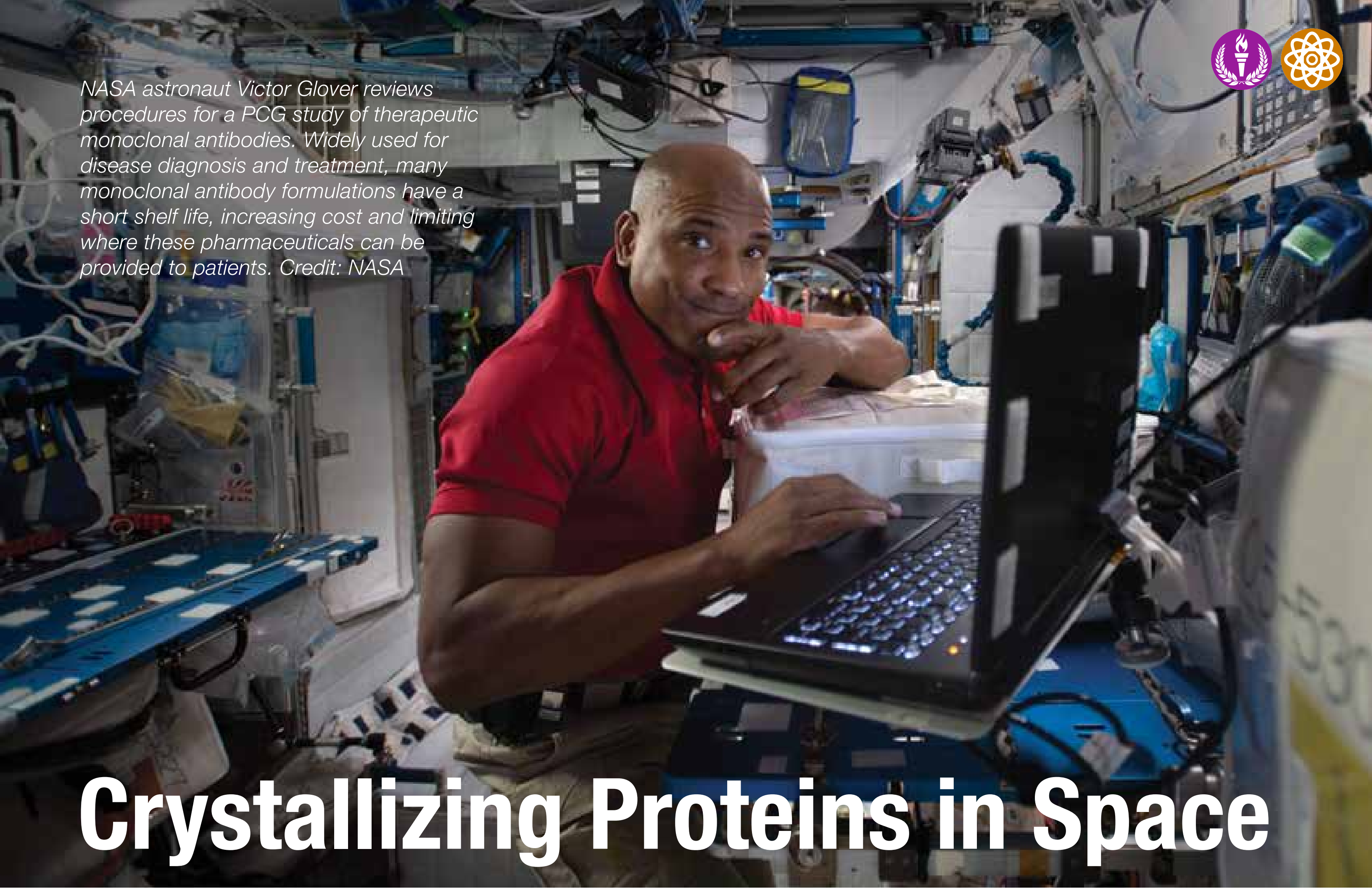
"A key take home is that blocking this pathway, which we knew would be effective in stimulating increased bone and muscle mass on Earth, is just as effective in microgravity," says principal investigator Se-Jin Lee at The Jackson Laboratory for Genomic Medicine in Connecticut. He explains that a number of drug candidates targeting this pathway already have been developed and tested in clinical trials, with mixed results. "One trial showed promising results, but the drug needs to be tweaked to avoid side effects. There is still a fair amount of work to be done to pursue this strategy for treating muscle loss. We have some amazing data on the magnitude of the effect on the ground and in space and hope it will stimulate a lot of drug development activity."

Increasingly, researchers from companies small and large, institutions, government agencies, and other organizations leverage microgravity to address complex human health issues on Earth. By providing a platform for long-term microgravity research, the space station fosters breakthroughs that yield direct benefits to people on Earth. Remove gravity from the equation and we can see out-of-this-world breakthroughs.

NASA astronaut Jessica Meir installs the Bone Densitometer that enables the imaging of rodent bones for Mighty Mice in Space. The investigation studies two proteins that may prevent muscle and bone loss in space. Credit: NASA

Additional space station research contributing to improved human health on the ground:

Project	Description	Benefits
ESA Brain-DTI	Tests the theory that the human brain uses previously untapped neural connections to adapt to space, examining changes in brain structure before and after spaceflight.	Results show significant differences in upper-brain structures pre- and post-flight that could affect long-term health and vision. A better understanding of neuroplasticity, or the ability of the brain to adapt, could advance other areas of neurological research.
ESA EDOS-2	Used a noninvasive technique tested in the EDOS investigation to examine whether astronauts continue to lose bone when they return to Earth and when recovery occurs.	Monitoring bone loss can inform diet and exercise programs used to counteract this loss in space and provide early detection of osteoporosis on Earth. The scanner used has already been successfully commercialized by Scanco Medical in Switzerland. The unique qualities of the scanner have led to its use in non-biomedical research applications, including nondestructive imaging of ancient Egyptian mummies.
ESA ETD	Examined how microgravity affects the ability to keep the eyes on a fixed point while tilting or shaking the head. This ability relies on the vestibular system, or inner ear and nerves that maintain balance and orientation.	The investigation used a special headset to track eye movement that proved ideal for tracking eye position in laser eye surgery without interfering with the surgeon, and is now being used in corrective laser surgeries throughout the world.
IGAR	Developed by the Canadian Space Agency and Centre for Surgical Innovation and Invention (CSii), this surgical robot acts autonomously after being programmed by a physician to perform highly accurate and minimally invasive procedures such as a biopsy.	A Phase I clinical trial showed IGAR is safe, accurate, and effective and CSii is working on final U.S. Food and Drug Administration (FDA) approval. The technology could be applied to imaging and treatment for a variety of cancers, including prostate and liver, and eventually enable remote emergency surgery in isolated environments or during natural disasters.
ESA MARES	A device that monitors muscle speed and force as astronauts exercise in an effort to determine muscle strength decreases during spaceflight.	The next generation of space exercise machines is likely to include variable counterforce capability, and MARES can be used for preliminary testing of the technique.
ESA MUSCLE BIOPSY	Analyzes expression of nitric oxide, a signaling molecule linked to muscle activity, in human skeletal muscle before and after spaceflight.	Improved understanding of loss of muscle mass in space could support development of more effective countermeasures for astronauts and provide insight into certain muscular conditions on Earth.



NASA astronaut Victor Glover reviews procedures for a PCG study of therapeutic monoclonal antibodies. Widely used for disease diagnosis and treatment, many monoclonal antibody formulations have a short shelf life, increasing cost and limiting where these pharmaceuticals can be provided to patients. Credit: NASA

Crystallizing Proteins in Space Helping to Identify Potential Treatments for Diseases

Crystals could make possible new and better versions of existing drugs to treat conditions from muscular dystrophy to cancer

Our bodies contain thousands of types of proteins. Proteins are involved in every aspect of our lives, including as essential components of our immune system and as part of viruses that can make us sick. When we take a medication, it binds to a specific protein in the body. This process changes the protein's function – and if it works properly, makes us well.

In many diseases, the proteins that can trigger the disease state fit into very specific locations, like a biological keyhole, and the protein of a potential drug for treating that disease must be designed to fit that keyhole. A good fit of key and keyhole results in a more effective medicine with fewer side effects. To achieve that fit, scientists need detailed knowledge of the structure of both proteins, and one of the best ways to analyze a protein structure is to grow it in crystalline form.

During the Space Shuttle and Mir programs, researchers discovered that they could produce higher quality protein crystals in microgravity than on Earth. For more than two decades now, the International Space Station has continued to serve as a platform for growing crystals for research purposes. Drug companies and academic researchers alike have conducted more than 500 protein crystal growth (PCG) experiments as of 2021 – by far the largest single category of experiments conducted on the station.

Determining the protein structure by X-ray diffraction requires the diffraction pattern from a protein crystal. The better a crystal diffracts X-rays, the more accurately this method can determine the structure of the protein. Since 2005, the Kristallizator program from the State Space Corporation ROSCOSMOS (ROSCOSMOS) has created single protein crystals especially suited for this analysis. Growing the crystals in microgravity significantly improves their quality and allows for greater three-dimensional resolution during analysis.

One outcome of the Kristallizator studies has been the growth of crystals that helped determine the structure of a target for anti-tuberculosis drugs. According to the U.S. Centers for Disease Control, more than 1 million people die from tuberculosis annually. It is difficult to treat because tuberculosis bacteria quickly adapt to medications. This ROSCOSMOS study revealed that the channel in the center of the molecule where the components of the reaction are bound changes its diameter during the reaction. Understanding this process could help scientists develop a treatment.

PCG research from many countries is showing promise for creating medications and treatments for a variety of diseases, including Duchenne Muscular Dystrophy (DMD), a currently incurable genetic disorder. A Japan Aerospace Exploration Agency (JAXA) study of the crystal structure of the protein associated with DMD provided hints for compounds that could inhibit it. Yoshihiro Urade, professor at the University of Tsukuba in Tsukuba, Japan, used those hints to design several promising compounds, including TAS-205. A 2015 study verified the safety of TAS-205 for use in humans, and a clinical trial in human patients was completed in 2017. The research team estimates the drug may slow the progression of DMD by half, potentially doubling the lifespan of many patients.

Co-investigator Mitsugu Yamada of JAXA says a larger Phase 3 trial to examine the effectiveness of TAS-205 in situations similar to actual clinical use began in December 2020 and will continue until 2027.

Overall, the JAXA PCG investigation has studied protein crystal growth in microgravity for more than 20 years, providing precise structures of many protein types and leading to the discovery of potential drugs for breast cancer and periodontal or gum disease in addition to muscular dystrophy. While details are yet to be disclosed, Yamada says development of those drugs is going well, with some in preclinical trials.

In addition to creating completely new treatments, PCG research on station can lead to the formulation of drugs that are easier to store and last longer. For example, formulas that are stable at room temperature for long periods of time eliminate the need for refrigeration, lowering cost and simplifying distribution. Refrigerated drugs degrade over time and sometimes must be discarded, also increasing cost and limiting access for patients. An investigation sponsored by the International Space Station National Laboratory, CASIS PCG 19, examined the stability of monoclonal antibody formulations. Monoclonal antibodies are drugs made from large, complex molecules taken from living organisms such as microbes or human or animal cells. CASIS PCG 19 could reveal the processes that lead to their degradation and, ultimately, help identify ways to slow it down.

Also sponsored by the ISS National Laboratory, PCG-5 focused on another aspect of drug formulation: how a drug is given to the patient. The study worked to grow a more uniform crystalline form of the monoclonal antibody Keytruda®, which is used to treat several types of cancers, including melanoma and lung cancer. Monoclonal antibodies do not dissolve easily in liquid. That makes it difficult to create a drug that can be given via an injection in a doctor's office rather than having the patient spend hours in a clinic setting to receive the drug intravenously. PCG-5 produced high-quality crystalline suspensions that could make possible delivery of Keytruda® by injection, not only making treatment more convenient for patients and caregivers, but also significantly reducing cost.

Based on the success of PCG-5, Reichert and his team conducted a follow-up experiment, PCG 20, on the space station in 2022. PCG 20 investigated other variables in microgravity with additional methods targeted at understanding how to create higher order, purer, and more uniform crystalline suspensions of Keytruda®

JAXA astronaut Soichi Noguchi works in the JAXA Protein Crystal Growth (PCG) Glove Bag to mix a sample for the JAXA Moderate Temperature Protein Crystallization Growth experiment. Credit: NASA

ESA astronaut Thomas Pesquet removes canisters from the Protein Crystallization Research Facility (PCRF) for handover to ROSCOSMOS cosmonaut Oleg Novitskiy. Image was taken during JAXA-PCG and Kristallizator experiment operations. Credit: NASA

"The research team estimates the drug may slow the progression of DMD by half, potentially doubling the lifespan of many patients.

on Earth. This work is ongoing, as is research on other potential therapeutics, according to principal investigator Paul Reichert of Merck Research Laboratories.

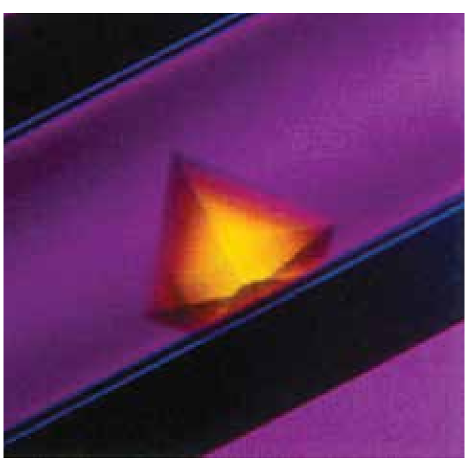
Reichert has been involved in microgravity research for more than 25 years, first aboard the space shuttle and then more advanced research aboard station. He says he uncovers something new with every experiment. “It is the unexpected that keeps me coming back.”

He focuses on using his experiences and results to promote use of the space station for research by others.

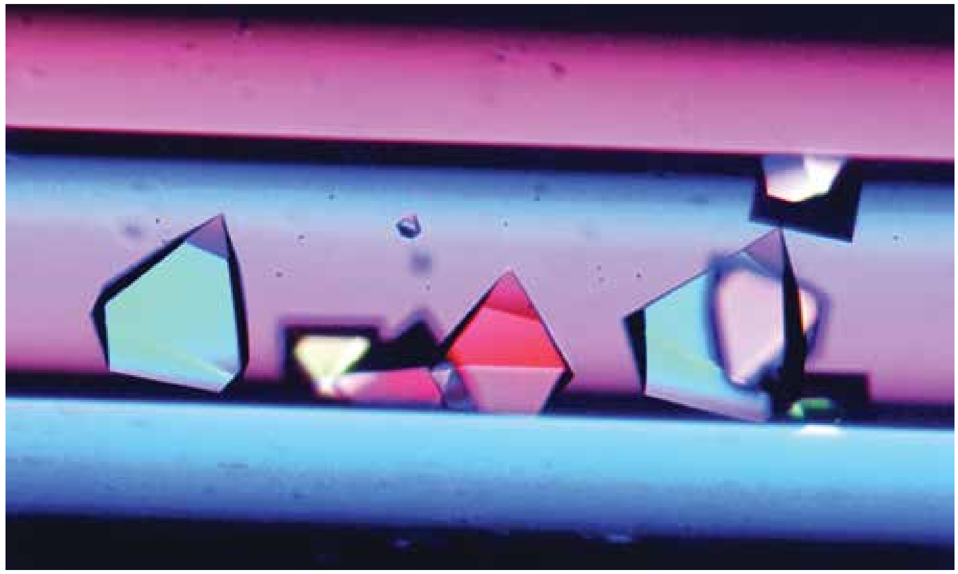
“The Merck team developed simple research hardware and processes for our own research and to entice a broader group of scientists from other disciplines into microgravity research,” Reichert said. “We also design experiments such that we can publish our results to the research community and general public. I think there are a lot of microgravity research opportunities and I am going to continue to try to encourage people in diverse scientific areas to think about how they could benefit and learn from doing microgravity research.”

JAXA also has worked to increase interest in PCG research.

“In recent years, we have been developing membrane protein crystallization technology and are preparing to provide it as a standard service to many researchers,” Yamada says. “We believe that this will lead to further results from space experiments.”



A crystal structure of E. coli *thymidine phosphorylase is shown. Credit: ROSCOSMOS*



Protein crystals formed in microgravity in the space station’s Kibo Module. Credit: JAXA

STS-61C payload specialist and then-U.S. Representative Bill Nelson (D-Florida) prepares to photograph samples of the Handheld Protein Crystal Growth (HPCG) Experiment on space shuttle Columbia. Credit: NASA

In addition to showing promise in drug development, the JAXA work on crystallizing proteins in microgravity inspired development of an artificial albumin. Albumin is the most abundant protein in blood, but it is difficult to crystallize on Earth. Researchers used the space station to crystalize albumin from cats and dogs to better understand the structures of these proteins and how they are made. The work has potential applications in veterinary medicine.

“Human serum albumin preparation is manufactured from donated blood and is widely used in clinical practice,” says Teruyuki Komatsu, a professor at Chuo University in Japan and co-author on a paper reporting the results. “There is no Red Cross Society for dogs and cats, though, and veterinarians in animal hospitals have trouble providing blood transfusion treatments. This could help solve the shortage of animal blood.”

The artificial albumin must be manufactured in large quantities with high purity, and so far, cost has prohibited large-scale testing in animals, Komatsu explains.

Other studies aboard the space station advance the field of protein crystallization itself. The LMM Biophysics-2 experiment team found a new, faster process for growing high-quality crystals of an antipsychotic drug aboard the space station. This process could provide a better understanding of the underlying chemistry of the drug and lead to improved medications to treat psychiatric disorders.

Availability of the space station as a platform for growing high-quality protein crystals continues to be key to bringing people on Earth new and better treatments for diseases.

NASA astronaut Kate Rubins works on the Cardinal Heart study, which seeks to help scientists understand the aging and weakening of heart muscles in the search for new treatments for astronauts and people on Earth. Credit: NASA

Tissue Chips Investigate Diseases, Test Drugs on the Space Station

Small devices that mimic functions of human organs help researchers understand the progression of various diseases and provide a faster and safer alternative to preparing drugs for clinical trials.

Tiny canisters of beating human heart cells that flew on the International Space Station could help scientists understand abnormalities in heart cells and tissues that can lead to disease on Earth. The Cardinal Heart investigation used these engineered heart tissues (EHTs), a type of tissue chip, to examine how microgravity affects heart cells.

Tissue chips are small devices containing living cells that mimic complex functions of specific human tissues and organs. In microgravity, cells assemble differently than they do in laboratories on Earth and behave more like they do when inside the body. That makes the space station a unique platform for studies using these devices. Tissue chips also make up an important aspect of tissue engineering, which uses a combination of living cells and other materials to restore, maintain, improve, or replace biological tissues.

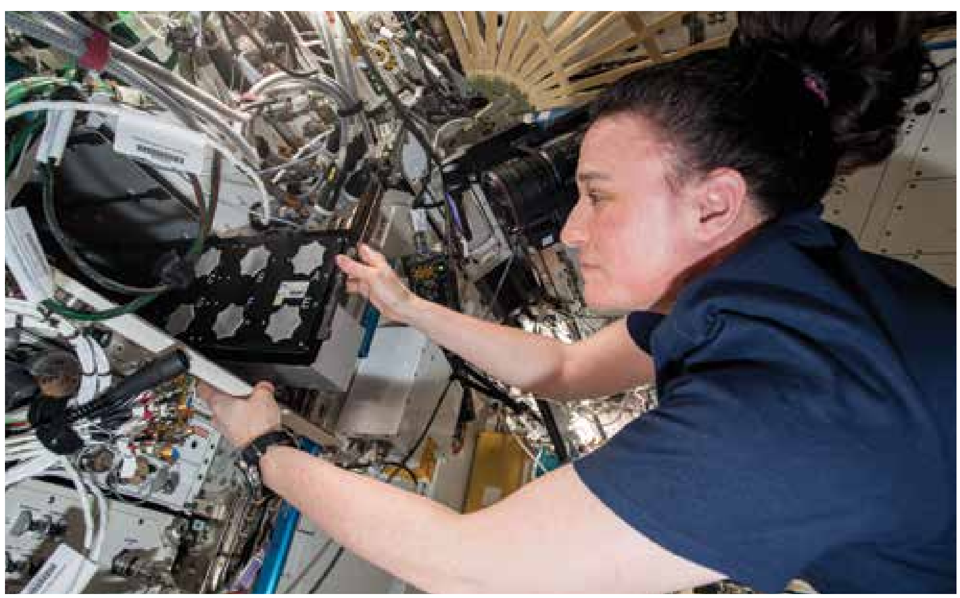
Cardinal Heart confirmed that microgravity caused changes to the EHTs. The next step, explains principal investigator Joseph Wu, director of Stanford Cardiovascular Institute, is testing whether certain drugs can prevent these altered effects during spaceflight and, eventually, help people with problems such as cardiac atrophy on Earth.

Using tissue chips to test the effect of drugs could help reduce the need for the animal studies that precede clinical trials in humans, currently the standard for approval of new drugs. Despite favorable results in pre-clinical animal studies, about 30% of medications are found to be toxic in human clinical trials and some 60% do not have the intended effect on humans.

"Tissue chips test potential drug candidates for human response and toxicity in a way that is more predictable," says Siobhan Malany, principal investigator for Human Muscle on a Chip, which tested the feasibility of using accelerated muscle weakness in space to study age-related muscle decline on Earth. "So many drugs fail because of a lack of human efficacy or because of toxicity. Tissue chip technology is really filling that gap from early discovery to the clinic. Because tissue chips are robust, three-dimensional, and micro-scale, we can send many of these experiments up for longer periods of time to observe long-term and chronic effects."

ESA (European Space Agency) developed its own experiment unit (EU) to culture cells in space. The SPHEROIDS investigation used EUs to examine the effects of microgravity on the function of endothelial cells. Endothelial cells line the inner surface of blood vessels and play a key role in vessel structure and regulation of blood pressure. Results published in the journal Biomaterials showed that endothelial cells formed 3D structures in the EUs with good viability for the 14-day test. The investigation also confirmed the functionality of the automatic medium exchange and fixation procedures. EUs could play a role like that of tissue chips in drug testing and research in pharmacology, toxicology, and radiation biology.

Malany plans a follow-up space station investigation to test whether a steroid



NASA astronaut Serena Auñón-Chancellor sets up for Culturing of Human Myocytes in Microgravity, an experiment aiming to better understand muscle growth and repair in microgravity. Credit: NASA derived from tomato plants, Tomatidine, improves muscle mass. "Basically, the same set of tissue chips will go back up to space. One gets the treatment and one does not, and we can look at specific responses and any toxicity," she says.

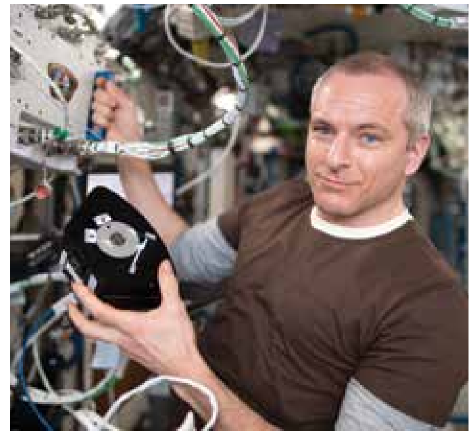
A type of tissue chip with human knee cartilage developed for a study of post-traumatic osteoarthritis (PTOA) is helping advance development of drugs to treat the condition. PTOA can occur when traumatic joint injury leads to loss of cartilage and bone. It affects millions of people of all ages and is believed to be initiated by a "cytokine storm," an over-response of the immune system following an impact injury such as a fall. International Space Station National Laboratory sponsored experiment MVP Cell-01 showed that low doses of dexamethasone, a potent anti-inflammatory, dramatically suppressed levels of cytokine in the knee following injury. A follow-up investigation combined the drug with a growth factor, and researchers plan to propose a clinical trial for the combination.

"Half of the drug development battle is discovery," says principal investigator Alan Grodzinsky, a professor in the Department of Biological Engineering at Massachusetts Institute of Technology. "The other half is drug delivery: in this case, a technique to get a low dose of the drug into the cartilage. We can use this chip system to test delivering the drugs with nanoparticles. Using a real human system has many advantages over using animal ones for these studies. In the not-too-distant future, this work should lead to treatments for PTOA."

Tissue chips provide faster results as well. "When you use a tissue chip platform, fabrication takes a few days," says Dilip Thomas, a post-doctoral researcher in Wu's lab at Stanford University. "Then, after you start treating it with drugs, depending on what measure you are looking at, you can have an entire set of data in one month."

Tissue chip studies on the space station take advantage of the fact that many of the changes that microgravity causes in the human body resemble aging-related diseases on Earth but happen much faster. Researchers can model changes in days or weeks rather than months or years.

"Microgravity accelerates disease processes and also uncovers potential new targets for drugs. We can look at disease pathologies in a way that we can't do here on Earth," says Lucie Low, scientific program manager at the National Institutes of Health's National Center for Advancing Translational Sciences (NCATS). NCATS partners with the ISS National Lab on the Tissue Chips in Space program, which funds these tissue chip studies. The program seeks to understand how microgravity affects human health and disease and to translate that understanding to improved human health on Earth.



Canadian Space Agency astronaut David Saint-Jacques processes samples for MVP Cell-01, which studies the effects of spaceflight on musculoskeletal disease as part of efforts to develop drugs to prevent Post-traumatic Osteoarthritis, a loss of cartilage and bone cause by a traumatic joint injury. Credit: NASA

STaARS BioScience-7 sent tissue chips to space to imitate aging of immune cells and confirmed that the cells age in microgravity and so provide a model for studying the process.

"We know the pathways involved, now we want to know whether we can prevent or even reverse the aging of immune system stem cells, which play a role in repairing our bodies and healing wounds," says principal investigator Sonja Schrepfer, a professor at the University of California San Francisco. Even young people can have aged immune systems, for example if a latent virus continuously activates the immune system. Schrepfer plans a follow-up experiment that will bring tissue chips back from space without freezing them.

"We know they will be aged, and we will look at whether we can reverse that back in the lab so that stem cells behave normally and repair a wound or blood vessels at normal speed. The goal is to fully understand a molecule that we can eliminate or a pathway to block to prevent aging effects," she says.

From the heart to the immune system, muscles, bones and more, these tiny stand-ins for human tissues are bringing about big results.

NASA astronaut Andrew Morgan services heart cell samples for the MVP Cell-03 experiment, which induces stem cells to generate heart precursor cells and cultures those cells on the space station. Credit: NASA

Astronaut Karen Nyberg, Expedition 37 flight engineer, performs an Ocular Health (OH) Ultrasound 2 scan in the Destiny laboratory of the International Space Station. Astronaut Chris Cassidy is visible in the background, assisting with the exam. Credit: NASA

Ultrasound Scans in Space Transform Medicine on Earth

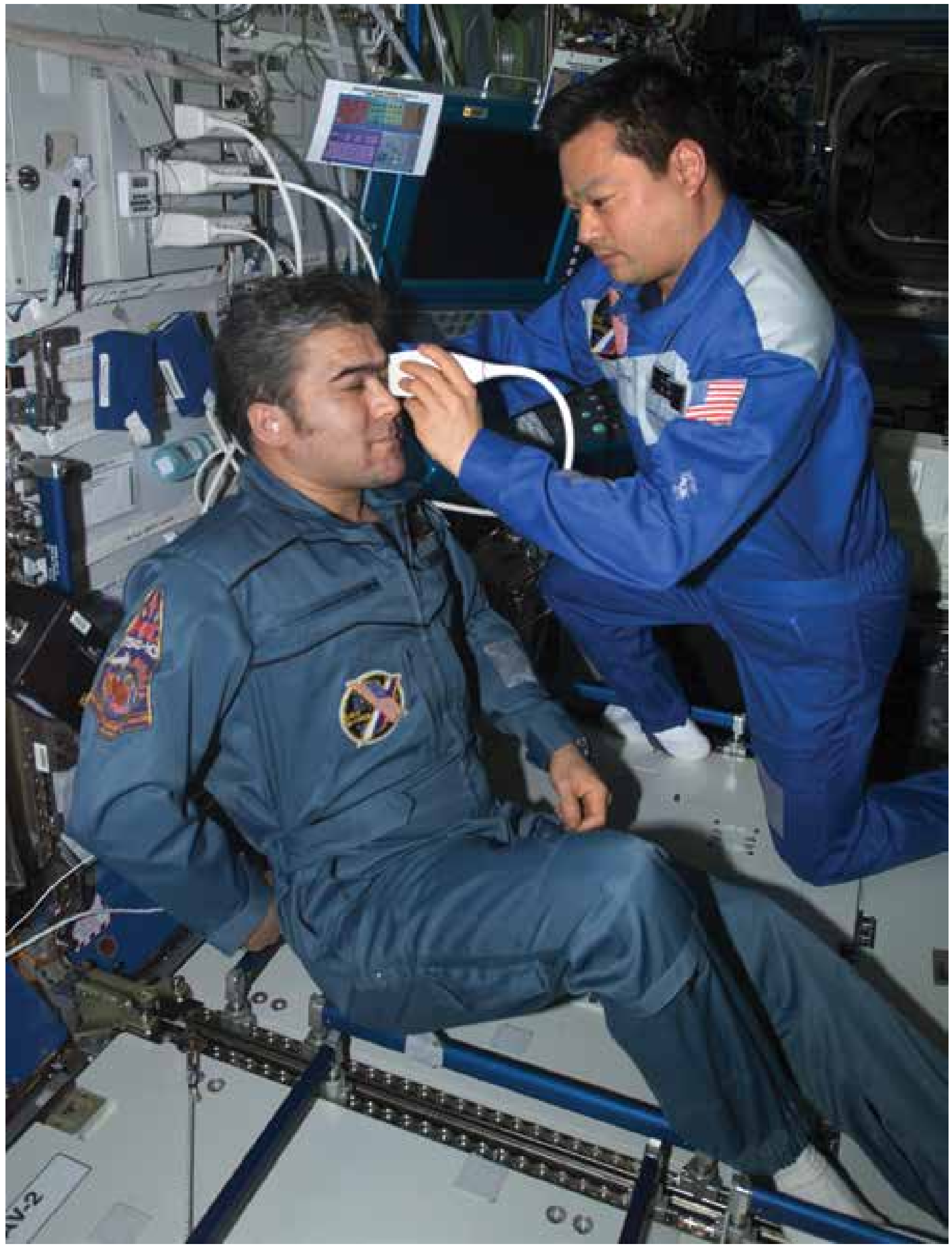
For people who live in major cities with fully equipped hospitals, access to quick and accurate medical imaging technology is not usually a problem. However, for those without medical facilities within easy reach, getting access to this technology can mean the difference between life and death.

For astronauts in orbit aboard the International Space Station, that problem was addressed through the Advanced Diagnostic Ultrasound in Microgravity (ADUM) study. Astronauts were trained to use a small ultrasound unit to examine fellow crew members. In the event of a health concern, astronauts can use this unit to diagnose many injuries and illnesses with the help of doctors on Earth.

In partnership with the World Interactive Network Focused on Critical Ultrasound (WINFOCUS), ADUM principal investigator Scott Dulchavsky took techniques developed for station

International Space Station Crew Surgeon Dr. James Pattarini and NASA astronaut Serena Auñón-Chancellor test the Butterfly IQ ultrasound in the medical tent at the landing site in Kazakhstan. Credit: NASA

WINFOCUS and Henry Ford Innovation Institute members, Dr. Luca Neri and Alberta Spreafico, work with Kathleen Garcia from Wyle Engineering to help train Dr. Chamorro from the rural community of Las Salinas, Nicaragua, using the ADUM and tele-ultrasound applications. Credits: WINFOCUS/ Missions of Grace



Using ADUM protocols, NASA astronaut Leroy Chiao performs an ultrasound examination of the eye on cosmonaut Salizhan Sharipov. Credit: NASA

astronauts and adapted them for use in remote areas on Earth by developing protocols for rapidly performing complex procedures with remote expert guidance and training.

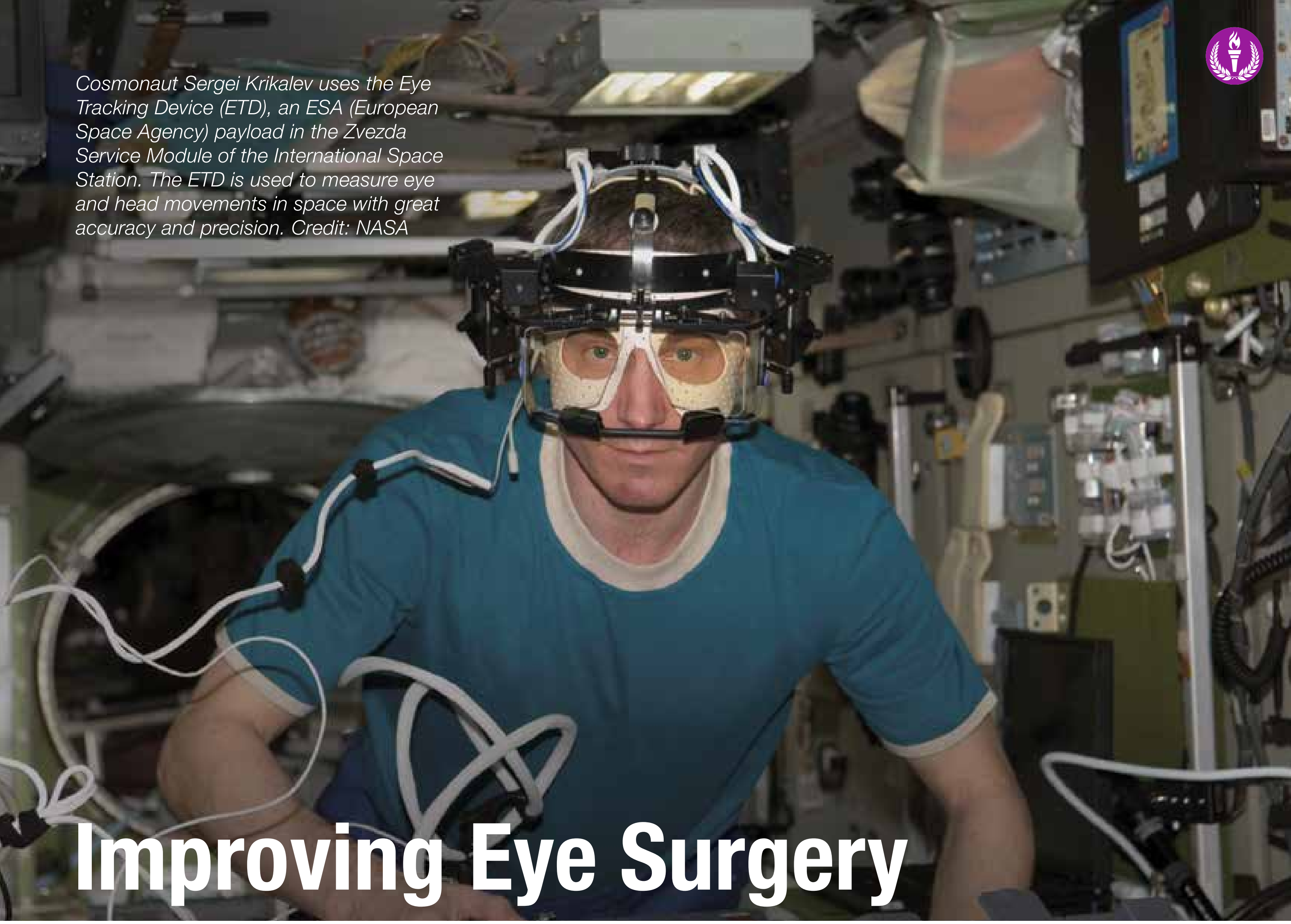
WINFOCUS has evolved the telemedicine and remote guidance techniques developed for use on the space station to allow use in large-scale healthcare systems on Earth through low-cost applications. Using the ADUM methods, WINFOCUS has trained more than 45,000 physicians and physician extenders in over 60 countries. As local healthcare providers are empowered, more patients can access quality and timely diagnostic care, and the healthcare system is made more efficient.

Sports medicine is also using these processes. Initially, ADUM-based ultrasound and remote guidance training were provided to non-physician athletic trainers for the Detroit Red Wings, Tigers, and Lions. These diagnostic capabilities were extended for use in the Olympic Games. An athletic trainer was remotely guided to perform a scan on a skier with an injured leg. The scan confirmed that she could continue to compete, and she won a gold medal three days later.

The impact of ADUM is even felt in emergency rooms by proving the effectiveness of ultrasound in diagnosing conditions previously considered beyond its technical capabilities, such as a collapsed lung. ADUM protocols have proven so effective that they are now part of the standard medical school curriculum: The American College of Surgeons, which requires ultrasound training for all surgical interns and residents, is using the ADUM program.

Building on this success, the upgraded Butterfly IQ Ultrasound is now being tested aboard station in preparation for deep space missions and in the field for taking data when astronauts return to Earth. Higher ultrasound image quality has historically been dependent on multiple probes and hardware too cumbersome for typical field conditions. Unlike past generations of ultrasound machines, Butterfly IQ has a single universal probe that works well on all organs, tissues, and blood vessels. The technology demonstration on the space station tests the use of this portable ultrasound in conjunction with a mobile computing device in microgravity. The investigation also collects crew feedback on ease of handling and quality of the ultrasound images, including image acquisition, display, and storage.

The combination of ADUM and new ultrasound technologies like Butterfly IQ will be a force multiplier for expanding access to diagnostic healthcare to areas previously left unattended, including deep space.



Cosmonaut Sergei Krikalev uses the Eye Tracking Device (ETD), an ESA (European Space Agency) payload in the Zvezda Service Module of the International Space Station. The ETD is used to measure eye and head movements in space with great accuracy and precision. Credit: NASA

Improving Eye Surgery with Space Technology

ESA astronaut Thomas Reiter conducts the Eye Tracking Device experiment on the space station in 2006. Credit: ESA

Laser surgery to improve eyesight is widespread, and technology developed for use in space is now commonly used on Earth to track the patient's eye and precisely direct the laser scalpel during the procedure.

The human eye can hold steady so a person can see a fixed point clearly, even while tilting or shaking his or her head. This reflex requires the brain to constantly interpret information from the inner ear to maintain balance and stable vision. An essential feature of this sensory system is the use of gravity as a reference.

The ESA (European Space Agency) Eye Tracking Device experiment researched mechanisms involved in this process and how the brain's frames of reference are altered in space. The experiment used a specially designed headset fitted with image-processing chips that track the eyes without interfering with the wearer's normal work. Results showed that balance and the overall control of eye movements are indeed affected by microgravity. These two systems work closely together under typical gravity conditions, but microgravity can cause them to become somewhat disassociated.

The engineers realized that in parallel with its use on the space station, the device had potential for applications on Earth, including tracking eye position without interfering with the surgeon's work in laser surgery. The Eye Tracking Device equipment is now used in many corrective laser surgeries throughout the world.

Space 24/7/365

View of Kayla Barron during pre-extravehicular activity operations during Expedition 66. Matthias Maurer and Mark Vande Hei are in the background. Credit: NASA

> *“I think there is no better possible training for Artemis and for our return to the Moon than being aboard the International Space Station.*
>
> *-NASA astronaut Kayla Barron*

NASA astronaut Victor Glover works with Honey, one of the free-flying Astrobee robots on the space station. The Astrobees support a variety of technology tests and demonstrations, including Astrobatics, which develops a new method of robotic propulsion. Credit: NASA

Technology Tested in Space is Preparing Us for the Moon and Mars

Robots, computers, health monitors, life support systems among the technologies advancing in space and on the ground

NASA astronaut Victor Glover spent six months aboard the International Space Station in 2020 and 2021. While there, he worked on technology demonstrations that could play a big role in future lunar exploration. As a member of the Artemis team, NASA's group of astronauts selected for missions to the Moon, Glover could directly benefit from those tests.

"I enjoyed looking at the design of experiments from an engineering standpoint," Glover says. "There is always the chance to do something more efficiently or use a tool differently, some little puzzle to be solved every day. I really enjoyed knowing that, as crew members, we help advance technology to take us farther into space and improve life on Earth."

The space station offers a unique platform for trying out new technology in space. Expertise and hands-on experience gained by astronauts and cosmonauts working and living in space long-term provide an added benefit for future missions beyond low Earth-orbit.

One investigation on which Glover worked, Astrobatics, uses the space station's Astrobee robots to demonstrate robotic propulsion via hopping or self-toss maneuvers.

Robotics have a wide range of applications inside and outside a spacecraft. Currently, these automated helpers use fan-based propulsion, ducted fans, or zero-g climbing, which involves grasping handrails with robotic manipulators. Hopping requires less maneuvering, can be faster, and allows a robot to avoid areas that cannot be traversed using microgravity climbing, such as those without sufficient holds or with obstacles.

"People all over the world worked on Astrobatics," Glover says. "We all approached it as, 'We are going to learn something.' The Astrobees are great. They are modular, so we can put different systems and parts on them. That technology and that team are a pleasure to work with."

Human astronauts have somewhat different needs from their robotic assistants, and researchers have tested a number of technologies to monitor the health of crew members and keep them safe on long spaceflights. Canadian Space Agency (CSA) astronaut David Saint-Jacques was the first to test the CSA's Bio-Monitor, a system using wearable sensors to monitor crew health without interfering with daily activities or taking up a lot of time. The technology includes a smart shirt and dedicated tablet application.

Bio-Monitor records the wearer's physical activity, heart rate, and respiration; takes regular blood pressure readings; and estimates arterial stiffness. Researchers can use these data to assess an individual's metabolism and vascular health, and perhaps identify and detect biomarkers that may predict early signs of cardiovascular aging.

Canadian Space Agency astronaut David Saint-Jacques testing the Bio-Monitor, wearable technology designed to measure and record astronauts' vital signs. Credits: CSA/NASA

"The Bio Monitor is a one-stop shop for tracking what is going on with our bodies," says Saint-Jacques. "Similar technology could eventually be used to monitor athletes, workers in dangerous environments, or patients in remote localities on Earth."

A primary hazard of spaceflight – for people and equipment – is radiation. The AstroRad Vest investigation tests a vest designed to protect astronauts from radiation, gathering feedback from astronauts about how easy the garment is to put on, its fit and feel, and the range of motion it allows. AstroRad complements MARE, a partnership involving NASA, the Israel Space Agency, and the German Aerospace Center (DLR), to characterize the radiation environment astronauts are expected to experience on Artemis-1.

A variety of other technologies add to radiation protection, including a study called A-HoSS that evaluates the performance of a radiation detection system in space. Another space station study converts radiation measurements into risk levels for specific places and times aboard the space station.

As important as addressing hazards to humans in space is providing them with essentials such as air and water. Life support systems, including ways to provide adequate water, are another critical part of space travel being tested and tried on the space station.

NASA astronaut Megan McArthur with Spaceborne Computer-2, which explores how commercial off-the-shelf computer systems can advance exploration by processing data significantly faster in space with edge computing and artificial intelligence capabilities. Credit: NASA

AquaMembrane, an ESA (European Space Agency) investigation, tests replacing the station's current water recovery system with an apparatus called the Aquaporin Inside Membrane (AIM). More-efficient water reclamation systems could reduce launch mass and associated costs for space travel.

UWMS demonstrates new and improved toilet technology on the station.

The central design concept can be easily integrated into different spacecraft, such as for future missions to the Moon and Mars. Another UWMS unit will be installed in Orion for the Artemis II flight test that will send astronauts on a mission beyond the Moon and back. A smaller, more-comfortable, and more-reliable waste-disposal method frees up time for the crew to focus on other activities.

Melding waste disposal and providing water, the Exploration ECLSS: Brine Processor System demonstrates a way to recover more water from urine.

A urine processor assembly that is currently part of the station's water recovery system recovers about 93.5% of water from crew urine and condensate in the cabin. Crews on long-duration exploration missions will need to recover closer to 98% of the water they bring along on their journeys. Current urine water recovery systems use distillation, which produces brine. The Brine Processor extracts the remaining water from the brine, bringing overall water recovery closer to the 98% requirement.

In 2018, crew members also installed ESA's Life Support Rack to test technology for recycling carbon dioxide into oxygen. It features a slightly different design than NASA's existing system, which is based on ongoing tech

A full Moon as seen from the International Space Station, visible in the foreground. Credit: NASA demonstrations that react collected carbon dioxide with hydrogen to make water. Prior to development of these systems, the station relied on water shipped from Earth to generate breathing oxygen. The technology therefore represents a huge step toward developing sustainable life-support systems needed for longer missions.

With robot performance tested and people protected, a next step is ensuring that both can do their jobs as quickly and efficiently as possible. The ISS National Laboratory and Hewlett Packard are testing a high-performance commercial off-the-shelf system to move computing power into space.

"Many experiments that run on the space station primarily collect data and send it back to Earth," says Mark Fernandez of Hewlett Packard, principal investigator for Spaceborne Computer-2. "We want to move computing to where data are generated or collected, whether that is in space, or on your oil rig or aircraft, to turn a sample into insight as fast as possible. You process at the edge and get the go or no-go or safe-unsafe answers you need."

This study builds on previous space station research, ensuring this type of computer system can operate without extensive protections against radiation.

"The purpose of exploration is not data collection, it is insight, and I want to get brilliant minds throughout the world working on the insight rather than crunching numbers," Fernandez says. "This capability does not change anything that a scientist already does, it just moves it nearer where the data are generated. The depth of the potential is pretty deep – things like image and signal processing, health care, DNA analysis."

Deep space missions do not all take place inside carefully closed-off habitats, of course. Sometimes astronauts must work outside spacecraft and habitats and their carefully planned life support systems – work that relies on spacesuits. SERFE conducts a new technology demonstration using water evaporation to remove heat from spacesuits, investigating the effect of contamination and corrosion on the thermal control system and examining how microgravity affects the system's ability to regulate

Bringing Space Technology Benefits Down to Earth

For NASA astronaut Victor Glover, potential benefits for people on Earth are one of the most important aspects of research and technology demonstrations conducted on station.

"We astronauts give constant feedback to investigators and developers," he says. "It is not just a piece of technology; it is a piece of technology that will be used by someone. How we humans interact with it is a valuable part of the learning. Everything we do has applications on Earth."

For example, Glover's work on advanced mobility for robots on the space station could enable reconnaissance drones to reach places they previously could not. Technologies developed to protect astronauts from radiation in space also could protect people in medical settings, first response to disasters, and the nuclear industry on the ground.

Cardiovector, a State Space Corporation ROSCOSMOS (ROSCOSMOS) investigation of cardiovascular system adaptations in microgravity, employs a unique device to capture central pressure and blood flow velocities in cosmonaut aorta. The device has been employed on the station for several years and may have wide applications in assessing cardiovascular health on Earth.

A Canadian company called Hexoskin, which helped develop a material used for the CSA Bio-Monitor investigation, is working on using the technology for remote monitoring on Earth as well.

"Health monitoring in real-life contexts is essential for improving the quality of care, and remote monitoring should be a fundamental component, considering the geography and demography of Canada, the United States, and other countries," says Hexoskin co-founder Jean-François Roy.

"One of our goals is to help patients go home from the hospital as soon as possible while still monitoring them adequately," he adds. "Our model provides a continuum of care where every patient is monitored and supervised at home as if they were still in the hospital. Health care systems are adapting to managing health long term and increasing patient involvement in their own care. A wearable monitoring technology helps enable this transition."

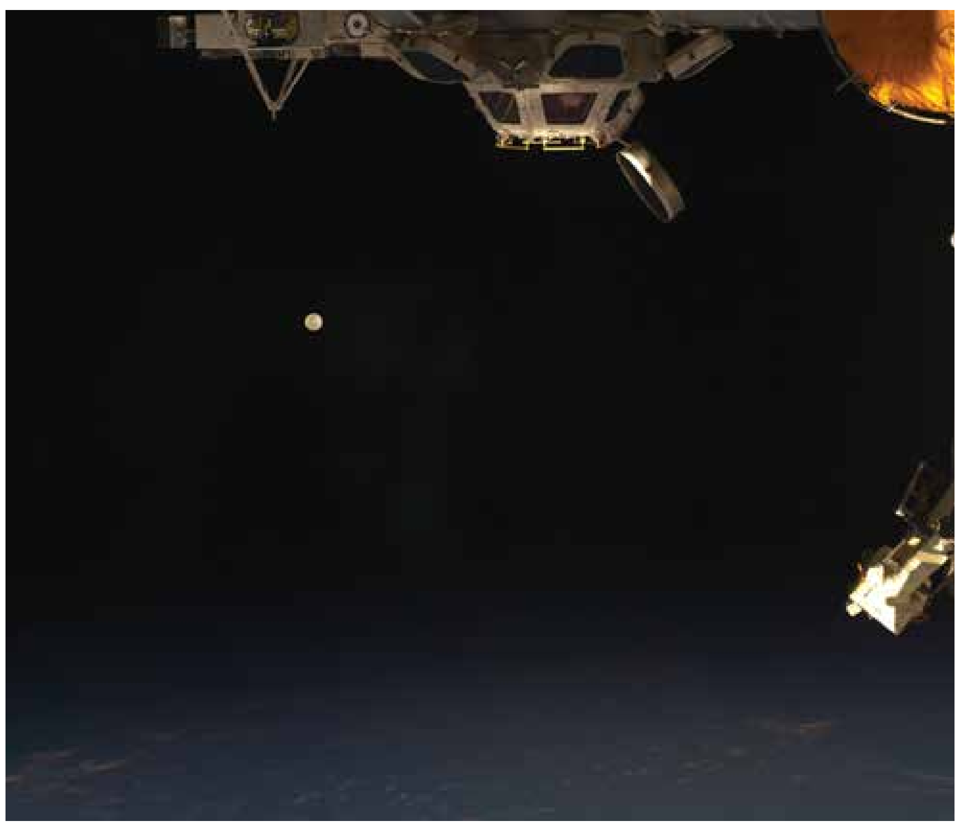
ESA's AquaMembrane investigation also has the potential to benefit people on Earth. Facing a growing scarcity of fresh water around the planet, scientists are turning to a process called desalination, which removes salt from seawater and brackish water. The AIM technology used for AquaMembrane is especially suited to a desalination process called forward osmosis that has shown promise in ground testing. Technology used to recover water from urine brine for space crews also could help provide water for people in harsh and remote settings with limited access to water on Earth.

NASA astronaut Serena Auñón-Chancellor operating a sextant in the space station's cupola for the Sextant Navigation investigation. Credit: NASA

astronaut body temperature under various conditions, such as physical activity and changing temperatures.

The final step of a successful mission – coming home – relies on navigation systems and their back-ups. Sextant Navigation successfully demonstrated that a hand-held sextant could provide emergency navigation on future exploration missions. Much like Glover, NASA astronauts Serena Auñón-Chancellor and Anne McClain and ESA astronaut Alexander Gerst each brought their expertise to using the tool aboard the space station. They added additional reference points to account for the speed at which the space station moves, found comfortable ways to steady themselves while using the instrument, tested red-text versions of star charts on a tablet, and made other adjustments.

"As a test pilot, I know how important it is to test systems in the environment where they will be used," Glover says. "Taking something up to the station and showing it can survive there helps us make things that last longer here. It is vital to have this capability."



A view of Earth airglow showing NASA astronaut Don Pettit gazing out through the Cupola module windows with the Moon visible in the background. Credit: NASA

ROSCOSMOS cosmonaut Oleg Novitskiy uses the Fundoscope during an eye examination for the Fluid Shifts experiment. Credit: NASA

Human Research: Astronaut Physiology

NASA astronaut Michael Barratt reads a checklist while performing a check of the SPHERES Beacon Tester aboard the International Space Station. Barratt wore slightly stronger pairs of glasses while in orbit to counteract vision changes he experienced during his time in orbit. Credit: NASA

NASA astronaut Michael Barratt flew a 6-month mission aboard the International Space Station in 2009. As the days went by, Barratt and fellow crew member Canadian Space Agency (CSA) astronaut Robert “Bob” Thirsk began having trouble reading the procedures for scientific research conducted on the orbiting lab. Slightly stronger pairs of glasses solved their problem, but the two, both physicians, decided to look deeper.

They found symptoms of what is now known as Spaceflight Associated Neuro-ocular Syndrome (SANS). Classic symptoms include swelling in the optic disc, which is where the optic nerve enters the retina, and flattening of the eye shape. When researchers looked back, they found certain aspects of SANS in even the earliest spaceflights.

More than 500 people have gone to space, but far fewer have stayed for long-duration missions. That makes data on astronauts like Barratt and Thirsk, and the changes their bodies go through, precious information. An astronaut’s body goes through a variety of adaptations to adjust to the unique environment of space.

“As soon as you get into the weight-lessness, everything starts lifting up and you just feel this sensation. It is

Canadian Space Agency (CSA) astronaut Bob Thirsk gives his crewmate ESA astronaut Frank De Winne a helping hand with the ESA experiment Neurospat. The investigation recorded astronaut brain activity to assess how three-dimensional navigation and visual perception skills are affected by long-duration stays in microgravity. Credit: CSA

such an extraordinary feeling, and physiologically it feels like when you are hanging upside down on the monkey bars at the playground," says NASA astronaut and physiologist Jessica Meir.

Monitoring SANS across station crew members has revealed that nearly 70% of them experience at least one of the hallmark signs, but with significant individual variability. Some crew members only experience these changes while in space, while some changes may be permanent for other astronauts.

Researchers now are studying the underlying causes and long-term health consequences of SANS and other neurological impacts to prepare for longer-duration missions. NASA's Fluid Shifts investigation evaluated a lower-body negative pressure countermeasure system and measured the impact of headward fluid shifts in microgravity, a suspected contributing cause of SANS.

"The idea of embarking on a long-duration flight to Mars without having made this discovery is mind-boggling," says Barratt.

Other studies, such as the ESA (European Space Agency) Neurospat and Circadian Rhythms studies, and the Italian Space Agency (ASI) Acoustic Diagnostics experiment, have explored other neurological effects of spaceflight. Neurospat recorded brain waves while astronauts completed tasks in a virtual reality environment to see if collected data backed up anecdotal astronaut reports of "space fog," a generalized cognitive slowing during their initial time in space. Researchers report that relative to before flight, astronauts made more errors and were slower to respond inflight and post flight and can now work to develop countermeasures and strategies to mitigate these changes. The Circadian Rhythms investigation examined whether long-term spaceflight throws off circadian or daily rhythm in astronauts and studied the role of factors such as irregular light and dark cycles, microgravity-induced changes in body composition, and reduced physical activity. Acoustic Diagnostics monitors astronauts' hearing health to determine whether there are adverse effects from noise and the microgravity environment of the space station.

The State Space Corporation ROSCOSMOS (ROSCOSMOS) study Algometry explored how pain thresholds in astronauts change in space. Preliminary data suggest a possible increase in the threshold during spaceflight. These data contribute to the understanding of fundamental aspects of the occurrence of pain and could support the optimization of methods for providing pain relief in space and on Earth.

Many unknowns remain concerning how future crews will adapt on upcoming missions to the Moon and Mars. Some challenges of living on the space station for six months will be different from those experienced for three years on a Mars mission. NASA's Human Research Program (HRP) has classified five major hazards to crew health summarized with the acronym RIDGE, short for Space Radiation, Isolation and Confinement, Distance from Earth, Gravity fields, and Hostile/Closed Environments.

"One of the biggest areas that we still need to understand more before we go further is how radiation affects the human body," said Meir. "We undergo and receive more cosmic radiation even when we're in the low-Earth orbit of the space station. When we go further, back to the Moon and to Mars, those levels will be even higher."

One landmark human research project aboard the space station, NASA's Twins Study, touched on numerous areas of astronaut health from cognition to fluid shifts to gene expression.

Understanding the Psychological Hazards of Spaceflight on the Space Station

In addition to research into the physical health of astronauts, scientists also use the International Space Station and low-Earth orbit to investigate the psychological and behavioral impacts of long-duration missions in space.

Isolation and distance from Earth present unique challenges when choosing a crew for missions to the Moon and Mars. The farther and longer we travel in these restricted environments, the more care must go into crew selection and preparation. The dynamics associated with mission length and distance are crucial to mission success, with communication, morale, and understanding among crew members vital to this achievement. NASA's Human Research Program (HRP) is investigating how a standardized assessment of behavioral health for space station crew can also help predict performance capabilities for future exploration crews once they land on the Moon or Mars.

Other examples of research into the behavioral health of crew members includes the following areas:

- Engaging in relevant, meaningful activities, including learning a language or learning new medical skills, have been found to help ward off depression and boost morale.
- HRP is examining the effects of tending to a space garden on the space station, which could have positive behavioral health benefits in addition to providing a fresh source of food and helping to purify the air.
- A collaborative CNES (French Space Agency) and ESA (European Space Agency) study, Immersive Exercise, tested whether a virtual reality environment for the station's exercise bicycle increases motivation to exercise and provides astronauts and cosmonauts a better experience for their daily multi-hour training sessions.
- Researchers are using Earth-based analogs to investigate how much privacy and living space will be needed on longer missions where crew members will be restricted in a relatively small spacecraft together.

Using this space station research, scientists aim to ensure that future space explorers will not only survive but thrive on their spacefaring missions. However, the same research and experience can be applied to informing how we address social isolation on Earth. For example, when 33 Chilean miners were trapped underground for more than two months,

ESA astronaut Thomas Pesquet tests out the equipment for the Immersive Exercise experiment on the ground before launch. Credit: ESA

NASA psychologists were part of a team deployed to help. Their experience in keeping crew mentally healthy in small, isolated spaces like the International Space Station helped rescuers support the miners in coping with their isolation, anticipate group dynamics, and manage any tensions that arose. The psychologists made recommendations for regular communications between the trapped minors and their families and provided counseling support for the families during the crisis and through the adjustment period as their loved ones returned home.

NASA Engineering and Safety Center principal engineer Clint Cragg (right) consults with Rene Aguilar (left), deputy chief of rescue operations for the Chilean mine disaster. Credits: Cecilia Penafiel, U.S. Embassy in Chile

The study brought together 10 research teams from around the United States to observe what changes could happen to a human from a year of exposure to spaceflight hazards.

Results published in 2019 compared a wide range of samples and measurements from astronaut Scott Kelly (now retired), who spent nearly a year in orbit from 2015 to 2016, to those of his identical twin brother, retired astronaut Mark Kelly, who remained on Earth. Some of the results included:

- The observation of the lengthening of Scott's telomeres, special features on the ends of each strand of DNA that typically shorten with age.
- Confirmation that Scott's body reacted appropriately to a flu vaccine administered in space. This allows NASA to have greater confidence that the immune system responds appropriately in space should a vaccine be needed during long-duration missions.
- Data supporting minor changes in gene expression. Most of these changes reverted after Scott returned to Earth, but a small subset persisted after six months. These findings help demonstrate how a human body adapted to space.

ESA astronaut Luca Parmitano participates in a hearing test aboard the International Space Station. The Acoustic Diagnostics investigation tests the hearing of station crew members before, during, and after flight. Credit: NASA

Overall, the Twins Study demonstrated the resilience and robustness of how a human body can adapt to a multitude of changes created by the spaceflight environment.

NASA astronaut Scott Kelly dons the Lower Body Negative Pressure device with assistance from Russian cosmonaut Mikhail Kornienko and ground support in Moscow and performs ophthalmic measurements. Such data collection provided crucial information supporting the Twins Study as well as many other human research studies during Kelly's year in space. Credit: NASA

Findings from the Twins Study may be used to develop new treatments and preventative measures for stress-related health risks on Earth. For example, telomere research may improve efforts to mitigate the effects of aging and disease, and protein research could have implications for studies on traumatic brain injury.

The microgravity environment also alters blood pressure control and vascular structures, which can have serious consequences for maintaining oxygenated blood flow to the brain and throughout the body. CSA has sponsored the Vascular, Vascular Echo, and Vascular Aging experiments to study vascular changes in astronauts with hopes of developing effective countermeasures to maintain astronaut health on future long-duration missions.

Data indicate that aging-like changes, including arterial thickening and stiffening, accelerate in many space station crew members. The most recent findings from advanced ultrasound studies of crew members also have shown increased wall thickness in the arteries.

"On Earth, people with type II diabetes have stiffer arteries because glucose stays elevated for a period of time after a meal, and that glucose then starts binding to proteins inside the artery wall and that causes an increase in stiffness," said Richard Hughson from the University of Waterloo, Ontario.

Similar impacts of insulin resistance may contribute to the signs of vascular aging observed in otherwise healthy and fit crew members. Other potential explanations may involve calcium deposits associated with bone loss or even oxidative stress from radiation. Effects from both hazards were well documented in the Twins Study as well and the Vascular Aging investigation continues to assess them. Uncovering the mechanisms behind these vascular changes may provide insights for developing interventions to slow aging and cardiovascular disease in older populations on Earth.

Results from another CSA study, MARROW, indicate that microgravity is a primary contributor to reduced red blood cell (RBC) count in astronauts, known as space anemia. The researchers found higher numbers of RBCs were eliminated in space than on Earth, and this change persisted throughout the duration of the space mission. Longer exposure to spaceflight appeared to worsen the condition. Elimination of RBCs sharply decreased upon astronauts' return to Earth. These findings may improve the health monitoring of astronauts and development of countermeasures to ensure safer space exploration.

Cardiovector, ROSCOSMOS' investigation, focused on blood pressure and propagation of the pressure waves within the aorta as another aspect of cardiovascular health in station crew. The data show consistent pulse wave propagation both in microgravity and in pre- and post-flight testing.

> "We are not only studying low-Earth orbit to understand it. We are studying low-Earth orbit as an analog for the Moon and Mars," said HRP chief scientist Steven Platts.

NASA astronaut Jessica Meir conducts an ultrasound for the CSA's Vascular Echo investigation, which examines changes in blood vessels and the heart while crew members are in space and after return to Earth. Credit: NASA

Continuing to study and understand how these stressors affect the human body is necessary to ensure astronaut health and performance for missions beyond low-Earth orbit.

"We are not only studying low-Earth orbit to understand it. We are studying low-Earth orbit as an analog for the Moon and Mars," said HRP chief scientist Steven Platts.

These human research efforts and many other future-facing projects all enhance life on Earth and beyond. Understanding the human component of human space exploration is paving the way forward to push to new limits and venture farther into space than ever before.

Canadian Space Agency (CSA) astronaut David Saint-Jacques collecting breath, ambient air, and blood samples in support of the MARROW investigation. Credit: NASA

Japan Aerospace Exploration Agency (JAXA) astronaut Koichi Wakata wears a sensor connected to the Thermolab Control Unit during Expedition 38. Credit: NASA

Heat Safety in Space

Keeps Infants and Patients Safe on Earth

Technology that measures body temperature, developed for the ESA (European Space Agency) Thermolab study, has begun to make a difference on Earth. Core body temperature rises faster during exercise on the space station than it does on Earth, and the experiment has investigated body temperature regulation and cardiovascular adaptations in crew members since 2009.

NASA astronaut Dan Burbank exercises on the Cycle Ergometer with Vibration Isolation and Stabilization (CEVIS) during a session of VO2max while Thermolab data are taken. Credit: NASA

The original investigation goal was to examine how body temperature patterns fluctuate in response to weightlessness. The specialized sensors, developed for the study by German company Dräger, have since been commercialized on Earth. The devices are deployed in many clinics to monitor infant incubators and patients during surgery. They have even been used to study how extreme heat affects farmers in Kenya and Burkina Faso. Other potential Earth-based applications include monitoring for signs of fatigue in people working in extreme conditions, such as firefighters and fighter pilots.

And, of course, this device also has contributed to our understanding of astronaut health. Compounding the problem of heat removal in space is a surprising finding from Thermolab that principal investigator Hanns-Christian Gunga described as “space fever.”

“In the first two months, the astronaut’s body temperature rises by one degree to 38°C (100.4°F), even in some cases a little bit higher,” said Gunga.

Paired with inflammation, this increase in temperature can be dangerous. Fortunately, space station research is helping us understand and monitor these changes to keep future crew members safe.

Tcore, a self-adhesive disposable sensor based on technology developed for space station research, is simply applied to the patient’s forehead. Credit: Dräger

So You Want to Be a Space Farmer…

Researchers are learning to grow plants in orbit to prepare us for living on other planets

NASA astronaut Mike Hopkins transplants pak choi in the agency's Vegetable Production System (Veggie) aboard the International Space Station on Jan. 14, 2021. Hopkins executed the first plant transplant within Veggie. Credit: NASA

While tending to a plant experiment inside the International Space Station, NASA astronaut Mike Hopkins noticed some of the plants were not doing so well. Although the mustard greens were growing fine in their special "pillows" containing clay-based growth media and fertilizer, some of the lettuces were not. "Outredgeous" Red Romaine and "Dragoon" lettuce seeds were germinating slowly, growing well behind the other plants. They would not catch up by harvest time.

With input from scientists at Kennedy Space Center in Florida, Hopkins executed the first plant transplant within NASA's Biological and Physical Sciences (BPS)-sponsored Vegetable Production System (Veggie). He moved extra sprouts from the thriving plant pillows into two of the struggling pillows.

On Earth, this transplant technique is risky for plants in this delicate state, and NASA had never attempted it in a space experiment. But it worked. The transplants survived and grew along with the donor kale and pak choi.

As humanity plans long-duration missions to the Moon and Mars, a key factor is figuring out how to feed crews during their weeks, months, and even years in space. What if astronauts could grow some of their own food in space?

Plants can provide crucial nutrients to supplement the prepackaged foods that can degrade in quality and nutrition after long-term storage. Researchers on Earth and crews aboard the space station are exploring the idea by testing various crops and equipment. By testing the plants in Earth orbit, we get to learn from unexpected surprises, like how to perform plant transplants, when the stakes are much lower.

"This little accidental transplant success is going to be pretty important; it opens up a lot of areas for future development," said Matt Romeyn, a space crop production project scientist and VEG-03I science lead.

There are many challenges to growing plants in space, from watering to providing plants adequate light and room to grow. Even a simple thing such as planting a seed in space was a technical challenge that required a new application of a well-understood technology. Using strips that dissolved in water like a breath freshener strip, Hopkins was able to easily plant lettuce seeds. Researchers like Anna-Lisa Paul, horticultural sciences professor and director of the Interdisciplinary Center for Biotechnology and Research at the University of Florida, have been working to overcome the many challenges presented to plants by space since the early days of station.

"In order to run an experiment on the ground, it might take you 10 tries, half a dozen graduate students, and who knows what else to get it exactly perfect. But if you send an experiment to the space station, not only does your experiment have to work the first time, you also must make it such that an astronaut with no gravity can do the maintenance, the harvest, and the data collection," said Paul.

Multiple space agencies have conducted station plant studies for decades. The Japan Aerospace Exploration Agency (JAXA) study, Bag Culture Experiment in the Japanese Experiment Module, helped demonstrate an engineering verification of a cultivation method using an aseptic bag culture. A series of 17 Russian space agency ROSCOSMOS (ROSCOSMOS) Rasteniya experiments studied how plants grow, develop, and reproduce in space in the Russian segment of station. NASA has successfully grown plants including lettuces and radishes and studied their response to space by analyzing everything from gene expression to spiciness. NASA's Plant Habitat-04

NASA astronaut Michael Hopkins smells Extra Dwarf Pak Choi plants growing aboard the International Space Station. The plants were grown for the Veggie study, which is exploring space agriculture to sustain astronauts on future missions to the Moon and Mars. Credit: NASA

NASA astronaut Peggy Whitson observes the Advanced Astroculture soybean plant growth experiment. Credit: NASA

experiment built on previous experiments to grow peppers in the Advanced Plant Habitat (APH). This became the longest plant experiment in space to date, growing for 137 days aboard the space station.

Seed studies have even gone outside of station as part of the Materials International Space Station Experiment (MISSE) project. The MISSE-SEED experiment exposed seeds from 11 different crops and model plants to the space environment for eight months. This was done to determine the effects from long-duration space exposure on seed quality and storage. This knowledge not only contributes to the ability for humans to one day explore Mars, but it can also have benefits to agriculture on Earth, since researchers are better able to understand specific plant responses to their environment.

Changes in gravity and the spaceflight environment can also affect how plants grow and how much produce they yield. One of the mechanisms plants use to sense gravity involves changes to calcium within their cells. JAXA recently ran experiments aboard the space station to measure how microgravity affects these calcium levels, which could offer clues for designing improved ways of growing crops for food in space. During a series of experiments using Biological Research in Canisters (BRIC), scientists performed studies on everything from plant organelles to better understand how plants sense gravity to studying genes that control responses to physical stresses like gravity.

Microgravity also presents a challenge when it comes to providing enough water to plant roots to keep them healthy without drowning them. Numerous experiments have tested a variety of methods to achieve this goal, including NASA's Veggie studies. The Veggie facility where Hopkins performed the plant transplant is a simple, low-power gardening chamber that can hold six crop plants. Crews then look after and water the plants by hand using syringes to inject water into the plant pillows. Plants ranging from Chinese cabbage to kale to zinnias have been grown in Veggie.

The NASA Plant Water Management studies hope to push plant growth facilities to the next level. The investigation demonstrates methods to take advantage of passive measures to control fluid delivery and uptake in plant systems. These methods include using surface tension, wetting, and system geometry to replace the role of gravity as a fluid delivery mechanism.

Using the Advanced Astroculture (ADVASC) system, station crews also successfully grew two generations of Arabidopsis plants, a model organism that is well understood and often used in fundamental biology experiments. The system provided precise control of environmental parameters for plant growth, including temperature, relative humidity, light, fluid nutrient delivery, and carbon dioxide and ethylene concentrations. The experiment showed the change in gravity caused seeds to be smaller and secondary branches and seed pods to grow differently.

Recognizing its potential for use in confined spaces on the ground, scientists adapted the ADVASC system for use in air purification on Earth. Initially used to prolong the shelf life of fruits and vegetables in the grocery store, the technology soon drew the attention of winemakers, who employ it in their storage cellars. According to one winemaker, the ADVASC-derived air purification system enhances storage conditions, resulting in even better wine.

“It is amazing when you think about all the innovations that are going on up in space, how they can come into a place as unexpected as a winery, which translates to benefits on your dinner table,” said Andrew Schweiger, winemaker at Schweiger Vineyards in St. Helena, California.

Multiple companies also now use this technology in air purifiers, which were shown to be effective in eliminating the SARS-CoV-2 virus. The companies have produced and distributed numerous purifiers during the pandemic.

Gardens need tending, which means growing veggies is about a lot more than the facility and plants themselves. Having humans aboard is a huge benefit to plants, especially when it comes to dealing with the unexpected. From Hopkins performing the plant transplant to NASA astronaut Megan McArthur hand pollinating chile flowers to former NASA astronaut Scott Kelly taking charge of the care of station’s zinnias when they began having difficulty growing, human tending and care has been crucial to plant success.

In addition to astronauts being a benefit to the plants, the greenery can also positively contribute to the behavioral health and well-being of astronauts. Many crew members report they find caring for the plants a fun and relaxing activity. NASA’s space crop production group is looking to gather data on this aspect by asking astronauts who currently cultivate vegetables on the station to each complete a survey about their space gardening experiences. For example, crew members who grow mizuna mustards take the survey two to three times for the month-long growth cycle of the plant.

“Crews really seem to enjoy growing the food themselves,” said Howard Levine, chief scientist for NASA’s International Space Station Research Office at Kennedy Space Center in Florida.

Left to right: NASA astronauts Mark Vande Hei and Shane Kimbrough, JAXA astronaut Aki Hoshide, and NASA astronaut Megan McArthur pose with chiles they grew aboard the space station. Credit: NASA

“It’s a nice reprieve from typical activities on the station, and astronauts often volunteer their free time to do it.”

What’s more, astronauts say the time spent gardening makes them excited to eat the fresh produce once it’s ready. The excitement motivates astronauts to use the produce creatively as ingredients in their meals, increasing their quality of life in space and boosting their morale. McArthur even created some tacos using fajita beef, rehydrated tomatoes and artichokes, and the fresh grown space station chiles. Other astronauts followed McArthur’s example, also making space tacos

NASA astronaut Victor Glover works on the Plant Water Management experiment that explored hydroponics as a future means to sustain plants in microgravity from germination through harvest. Credit: NASA

Plant scientist Lashelle Spencer (left) and research scientist Jason Fischer remove the stems from peppers that were grown inside the Space Station Processing Facility before weighing them in preparation for sending them to space. Credit: NASA

Russian cosmonaut Maxim Suraev, Expedition 22 flight engineer, holds Mizuna lettuce plants from the BIO-5 Rasteniya-2 (Plants-2) experiment in the Service Module. Credit: NASA

with chile peppers, and they expressed the same excitement at having fresh produce.

"Even though astronauts cannot run to the supermarket for fresh produce during a 2-year mission to Mars, they could float into a module that has the same smell and feel of the produce section," Hopkins said. "And that will put a smile on any astronaut's face."

While humanity is just now growing small crops in space, our understanding of these organisms has increased significantly thanks to station research. This understanding of plants is a crucial tool for pushing the boundaries of space travel.

"Plants are what allow us humans to be explorers, and venture past the limits of a picnic basket, regardless of whether you are transiting an ocean or a solar system," says Paul. "Learning about how plants respond to extreme and novel environments and how they grow under the challenges we will face when we take our biology off planet is one of the things that absolutely drives me. This is why I do this kind of work."

ESA astronaut Alexander Gerst floats beside packets containing wildflower seeds as part of the Space Seeds project. After the seeds returned to Earth, more than 12,500 German students registered to participate in the project by planting and observing the wildflowers. The project aimed to encourage students to appreciate biodiversity and inspire interest in space exploration and space technologies. Credits: ESA/DLR

Space Station Seed Studies Cultivate Student Scientists

Growing adequate food supplies during future missions to the Moon and Mars will put crew members' green thumbs to the test. But before going to these distant destinations, many questions remain unanswered in understanding how space affects plant growth. Scientists working on these challenges have recruited student investigators to engage the next generation of explorers and scientists.

A recent Space Seeds project invited schoolchildren across Germany to grow and observe wildflower seeds flown to the International Space Station. Through cooperation between ESA (European Space Agency) and the German Space Agency at DLR, the project attracted over 400 primary schools, transforming more than 12,500 third- and fourth-grade students into budding scientists.

"They will remember this for life," says Alexandra Herzog, the project's principal investigator from the German Space Agency at DLR, based in Bonn.

ESA astronaut Alexander Gerst also sent video messages along with the seeds to teach young students about the importance of biodiversity and preserving the planet. When Gerst and the seeds returned to Earth, each school received two seed packets to grow for a blind study: one set of seeds was exposed to space and the other remained on the ground. Unaware of which packet had been on the space station, students then recorded observations of both samples and sent an assortment of posters, videos, and letters directly to the German Space Agency.

"Most schools reported that the seeds that were on the space station, the 'space seeds', grew a lot faster and were bigger. The scientists at DLR believe that space travel stimulated the seeds," said Herzog.

Plans to repeat this experiment will explore these differences further. Accompanying research examining seed genetic differences will take place at the Helmholtz Centre for Environmental Research during the next iteration.

The Canadian Space Agency (CSA) has also inspired young students with

JAXA astronaut Soichi Noguchi poses with bags for the Tomatosphere investigation. Students grow the tomato seeds flown in space and measure germination rates. The project motivates students to pursue science, technology, engineering, and math (STEM) disciplines. Credit: NASA

a similar Tomatosphere™ project. Over the many flights of the project, thousands of students growing tomato seeds and measuring germination rates in their classrooms have provided valuable scientific data for scientists studying horticulture and environmental biology.

Additionally, NASA's Kennedy Space Center in Florida, in partnership with the Fairchild Tropical Botanic Garden, has provided students the opportunity to evaluate edible plant options for future space exploration. Called Growing Beyond Earth, the program has recruited more than 300 middle and high school classes across the United States to grow different crop types using special growth chambers to mimic the Veggie plant growth chamber aboard station. Students are testing the viability of multiple crops and provided data to NASA life scientists. The data continue to help NASA determine which plants to grow in space.

German third- and fourth-grade students work together to plant seeds returned from space at the kickoff event for the Space Seeds investigation. Participating schools received two separate packets of wildflower seeds—one sent to the space station and the other as a control. Students learned to think scientifically by recording observations of the gardens and reporting their observations to the German Space Agency at DLR. Credit: experimenta gGmbH

ESA (European Space Agency) astronaut Luca Parmitano, attached to the Canadarm2 robotic arm, carries the new thermal pump system that was installed on the Alpha Magnetic Spectrometer (AMS) during the third spacewalk to upgrade the cosmic particle detector. Credit: NASA

Learning by Living and Working in Space

In 2019, ESA (European Space Agency) astronaut Luca Parmitano was challenged to do something any kid (and most adults) would love to try: drive a remote-controlled rover from space. At the time, Parmitano was aboard the International Space Station and his task, dubbed ANALOG-1, was to see how well he could remotely command a robotic vehicle that was rolling around a course inside a building on Earth. This feat helps to prepare us for the day an astronaut could do the same type of task to explore the Moon, Mars, or other planets while orbiting above them.

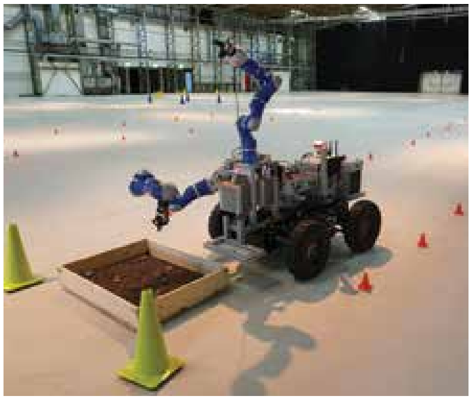
“A number of space agencies have looked at such a scenario for the exploration of planetary bodies – particularly for Mars,” said William Carey, ESA scientist and principal investigator for the ANALOG-1 experiment. “The approach could greatly increase the scientific return on those missions, as well as offer a way to avoid potential contamination from humans landing on the surface before we can answer questions about existing or previous life on Mars.”

For more than 20 years, space station experiments like this one have honed our ability to live in and explore space. To help crews thrive on the station, we have created new technologies, improved communications, conducted hundreds of spacewalks, studied astronaut health and well-being, and expanded the ability of many countries to support and collaborate on mission operations.

During Parmitano’s expedition, he also worked alongside NASA astronaut Andrew Morgan to save a scientifically valuable but failing piece of equipment outside the station, the Alpha Magnetic Spectrometer-02 (AMS-02). The project involved a series of spacewalks that took four years to plan and required developing more than 20 new high-precision tools. The process of creating the tools and procedures for these spacewalks prepares teams for the types of spacewalks that may be required on Moon and Mars missions.

“These are the kind of skills that are going to feed into going to a planetary surface,” said AMS spacewalk repair project manager Tara Jochim. “Cutting stainless steel tubing and then connecting new tubes on a thermal system during a spacewalk with the user-friendly mechanisms we have developed, all the while keeping it safe for the crew member, are the types of activities that will help create processes for tomorrow’s spacewalkers.”

To date, NASA has completed more than 200 spacewalks outside the space station. A key to completing many of them has been the Canadian Space Agency’s (CSA’s) iconic Canadarm2, a 17.6-meter (57.7-foot) robotic arm used extensively during assembly of



The ANALOG-1 Interact rover located near the European Space Research and Technology Centre in the Netherlands is controlled by a surrogate astronaut based at the European Astronaut Center in Germany. The cones mark out a route for the rover to follow to get to the sample site. Credit: ESA

the orbiting laboratory and to capture and move equipment and astronauts around the outside of the orbiting lab. Parmitano rode the robot arm to the location of AMS-02 during the repair mission.

The CSA will provide Canadarm3 to NASA's upcoming Lunar Gateway station, an outpost orbiting the Moon that will provide vital support for a long-term human return to the lunar surface, as well as a staging point for deep space exploration. Canadarm3 and Gateway are critical components of NASA's Artemis program.

The Canadarm technology is also the basis for a revolutionary medical procedure robot called IGAR. IGAR is designed to be paired with MRI scanners for breast cancer surgeries to remove small lesions before they become large tumors.

If Canadarm2 is the brawn of many station activities, the astronauts and teams on the ground are the brains. Together, they expertly collaborate to make repairs, conduct experiments, and ensure station operations go smoothly.

A significant part of successful collaboration, of course, is good communication.

NASA's Johnson Space Center in Houston works closely with international partners and Marshall Space Flight Center in Huntsville, Alabama, the site of the station's Payload Operations Integration Center, to execute research. Engineers and technicians at Marshall develop and test life support systems and conduct new studies of the space environment to make living aboard the space station sustainable. Johnson and Marshall communicate and coordinate 24/7 with the station and international partners to ensure missions are safe and successful.

The importance of this type of teamwork was on display in 2017, when crews aboard the station conducted an experiment to sample bacteria inside the orbital outpost and then sequence its DNA on the station – all while Hurricane Harvey raged over Houston. Technicians at Marshall connected scientists who were hunkered down in their homes in Houston with astronaut Peggy Whitson as she ran the experiment in orbit.

"Science aboard the station wasn't stopping because of Hurricane Harvey," said NASA microbiologist Sarah Wallace. "I thought 'Oh my gosh, I am watching the first sequence of an unknown from space.'"

Working together under adverse circumstances, the scientists coached Whitson through the first-of-its-kind process of sampling and identifying a microbe found in space without needing to send it back to Earth.

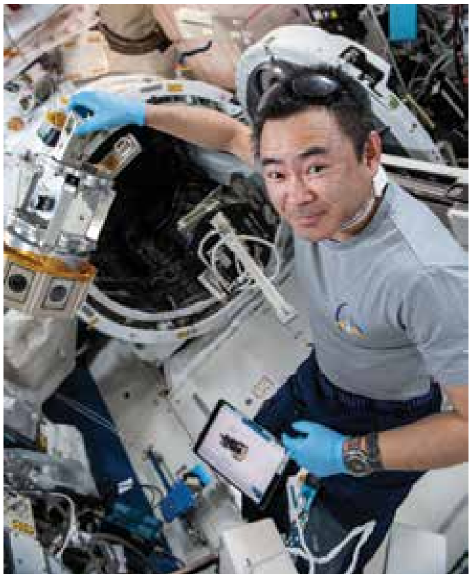
Supporting crew members has produced research that helps us understand how to protect and strengthen their mental health and teamwork on long-term missions. Researchers have learned about the effects of isolation, plants, food variety, and more on crew mental health. Crew experiences on station have even led to the development of the C-O-N-N-E-C-T concept to ensure crew members stay in good spirits and perform at their best by ensuring they take time to care for themselves and maintain a healthy mindset.

This work is done using a system of ground- and space-based communications networks and the combined knowledge of partner space agencies in dealing with challenges, such as those posed by interference from cosmic radiation, and delays in the time it takes for messages to be sent and received.

The technology of the communications system aboard the station was recently upgraded to double the rate with which information is transmitted to Earth, paving the way for similar capability on Gateway. This new rate enables the space station to send back more science data faster than ever before.

Communications also have been enhanced on the station using other spacecraft. The Japan Aerospace Exploration Agency (JAXA) HTV Wireless LAN Demonstration (HTV WLAN Demo) conducted real-time, wireless video transfer between the space station and a visiting spacecraft. Autonomous docking technology is important for future missions that will be unable to rely on human assistance. The experiment involved taking videos from a vehicle near the space

Left to right: NASA astronaut Andrew Morgan and ESA (European Space Agency) Commander Luca Parmitano work inside the Quest airlock checking U.S. spacesuits and spacewalking tools. The duo conducted several spacewalks to upgrade the Alpha Magnetic Spectrometer's (AMS's) thermal control system. Credit: NASA



Akihiko Hoshide of the Japan Aerospace Exploration Agency (JAXA) works in the Kibo laboratory module setting up a cinematic virtual reality (VR) camera to film station activities. The immersive ISS Experience VR series documents a variety of crew activities aboard the International Space Station for audiences on Earth. Credit: NASA

The Payload Operations Integration Center at NASA's Marshall Space Flight Center in Huntsville, Alabama. Credit: NASA

station and transmitting them to make astronauts aboard the station aware of the spacecraft's current position. The wireless link was established at approximately 548 meters (1,800 feet).

New types of video also are put to the test in space and could potentially capture future deep space missions. NASA, Canadian company Felix & Paul Studios, and TIME Studios developed Space Explorers: The ISS Experience, an immersive cinematic experience filmed by astronauts aboard station. The team designed special cameras to capture science and life inside the station, as well as a spacewalk outside. Testing the virtual reality (VR) camera technology used in the production on station prepares filmmakers for potentially capturing and transmitting high-quality footage from future missions to the Moon and other deep-space destinations. CSA has provided Felix & Paul Studios an investment to further develop this camera technology for lunar use.

"I think it is inevitable that VR is going to be the default way to document space exploration moving forward. It is a perfect match between medium and story," said Felix & Paul Studios co-founder and creative director Félix Lajeunesse. "Space exploration is something that you want to live. You want to be there. You want to experience it. Everything we're doing on station right now is a demonstration for the spaceflight industry and the entertainment industry of how we can use this medium moving forward in the space world."

By conducting missions aboard the space station, we are forging the ability to successfully send crews on flights that will take them farther into the solar system than they have ever been before.

"The International Space Station is one of the most ambitious international collaborations ever attempted," said Jim Morhard, former NASA Deputy Administrator, during an event commemorating the space station's 20th anniversary in orbit. "[It] is a convergence of science, technology, and human innovation that provides humanity with a one-of-a kind proving ground for Artemis as we go forward to the Moon and then on to Mars."

(Clockwise from bottom) Expedition 65 Flight Engineers Mark Vande Hei, Megan McArthur, Shane Kimbrough, and Thomas Pesquet work together as a part of robotics training in preparation to support two spacewalks. Credit: NASA

Bringing **Humanity** Along for the Ride

Flight Engineer Victor Glover, wearing a white flight suit, poses for a photo in front of the windows in the Cupola module. Credit: NASA

> *"We develop technologies and ways of using those technologies that are ways to improve life on Earth. But even more important than that I believe, space has a way of universally inspiring people. Making folks want to do very challenging things to the best of their ability is what I think human space exploration does most for humankind.*
>
> *-NASA astronaut Victor Glover*

A student stands at the microphone as he asks NASA astronaut Serena M. Auñón-Chancellor a question during the downlink event with NASA's Armstrong Flight Research Center. Credit: NASA

A Direct Link to Space

Inspiring the next generation through conversations with space

On Nov. 28, 1983, space shuttle Columbia launched, carrying former NASA astronaut Owen Garriott, amateur radio call sign W5LFL, and his ham radio into orbit for 10 days. For seven of those days, ham radio operators around the world, from classrooms to world leaders, heard Garriott's voice calling Earthbound ham radio stations. Thanks to a ham radio aboard the International Space Station, the conversations continue.

Amateur Radio on the International Space Station (ARISS) provides students from around the world the chance to ask questions directly to an astronaut in orbit, while learning the technical basics of ham radio operations. The program has now connected more than 250,000 participants with the space station and over 100 crew members.

"One of the primary purposes for the space station is to improve life here on Earth. That's not just from a biomedical standpoint or from a science standpoint. It's from an educational standpoint," said Courtney Black, education project manager for the ISS National Laboratory.

ISS National Laboratory education project manager Courtney Black stands in front of student Emily Gunger during an ISS ham radio contact between Lee County, Florida, students and space station NASA astronaut Serena Auñón-Chancellor. Credit: Andrew West/The News-Press

Before Black arrived at the ISS National Lab, she worked as a teacher for 14 years, bringing space education to her classroom. In the fall of 2018, she coordinated her district's first-ever contact, where 21 students from across Lee County, Florida, spoke with NASA astronaut Serena Auñón-Chancellor live from the space station.

Before the big day, the students spent many hours preparing. Every student learned the proper call signs and how to annunciate in addition to scientific lessons about energy and soundwaves.

"It was cool for me as an educator to see them grow and be confident, and the community rally around the group of ham radio operators who were taking their time to invest in a group of students and the impact it has had," Black said.

On the day of the event, the entire community gathered to cheer on these students for their eight minutes in the spotlight alongside Auñón-Chancellor. All 21 students got their direct connection to space.

"I can't explain the impact that it has when an astronaut takes the time out of their schedule for my students, to say you are important enough for me to answer your questions," Black said. "It means so much."

One of those students was then-high school senior, Emily Gunger.

On the day she spoke with station, she told her local news station, "This is the start of my career to become an astronaut. This is where I'm setting my foot down and saying, hey, this is what I want to do, and this is how I want to do it. This is it, let's do this."

A few years later, Gunger remains on that path, as she is now a student at Embry-Riddle Aeronautical University in Florida.

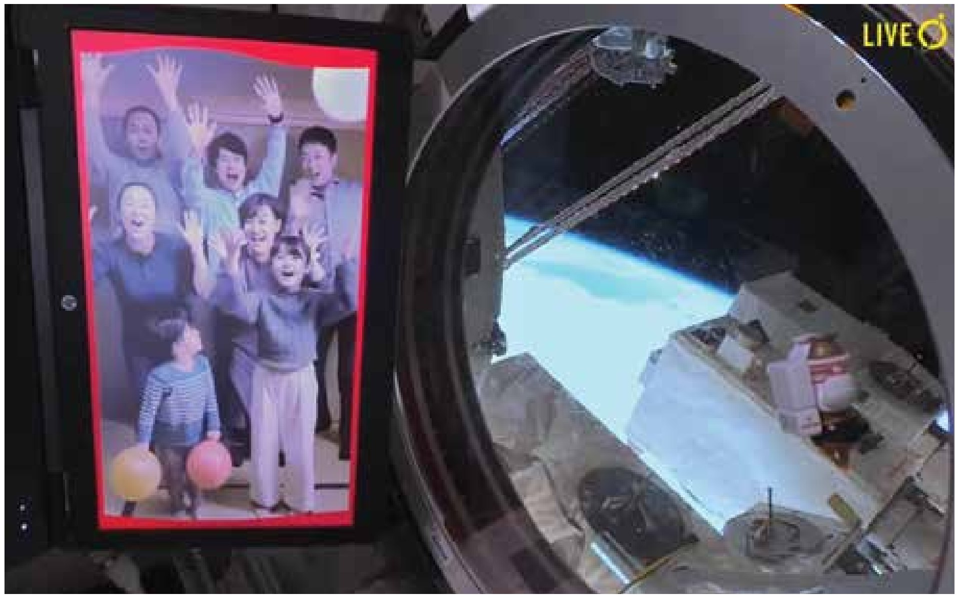
"Participating in this program motivated me to get a degree in Astronomy and Astrophysics," Gunger said. "It is so important to involve students in STEM fields and encourage them to ask questions."

This type of tangible connection to the orbiting laboratory has served as a spark for thousands of students around the world. Questions have been asked in more than a dozen languages. This all is possible thanks to the many international partners that sponsor the program in collaboration with NASA: the State Space Corporation ROSCOSMOS (ROSCOSMOS), Canadian Space Agency (CSA), Japan Aerospace Exploration Agency (JAXA), and ESA (European Space Agency). ARISS worked with CSA on Communications and Outreach 2 – ARISS, which connected CSA astronaut Chris Hadfield with a Canadian school.

ARISS also worked with ROSCOSMOS on the O Gagarine iz kosmosa (About Gagarin from Space) program, which involved transmitting photos dedicated to the life and work of the first cosmonaut. Over 20,000 images were transmitted during the experiment. More than 160 communication sessions were held with students from Russia as well as with amateur radio operators in countries including France, Ecuador, Brazil, Japan, Tunisia, Australia, India, and Greece.

The ROSCOSMOS Shadow-Beacon study even used the international network of amateur radio operators for an educational and scientific purpose. Participants did meaningful work, analyzing the quality of radio signals and effects of disturbances such as shading and elevation of the station. This provides a new tool to increase the timeliness and effectiveness of managing ground measuring networks.

Other programs have provided similar moments of connection with astronauts. Students record messages and images to send out to space with ROSCOSMOS's RadioSkaf program. Spot the Station email and phone alerts send families outside at night to watch the station pass overhead. More than 6,000 students accessed space station videos through the ROSCOSMOS outreach filming project, Velikoye Nachalo. A Raspberry Pi computer aboard station is used for an ESA livestreaming project called ICE Cubes Hydra-3 Pulse that transmits heartbeat data from museum visitors to the space station, where it moves a Kaleidoscope containing small beads.



A social media-submitted image is displayed next to a view out the space station window of Earth during the Studio Kibo 2021 New Year's Eve broadcast. Credit: JAXA

"The most important part of our job is inspiring the next generation," said Alana Bartolini, ISS and international education operations coordinator at Telespazio Belgium SRL for ESA. "What we want to do in this program is provide that access, that interest, and that inspiration for students at a young age and encourage them to take on more challenges as they get older."

Educational downlinks from the space station have directly reached hundreds of thousands of students, connecting classrooms and station astronauts for live conversations. JAXA's Space Studio Kibo is innovating on the downlink concept, bringing the accessibility of livestreaming from space to the ground through terminals in the Japanese Experiment Module (JEM).

"Anyone who has a smartphone can now connect with the space station," says Rumiko Nango, producer and project director at Bascule Inc., the developer of Studio Kibo.

One of the largest Studio Kibo projects to date livestreamed the first space sunrise of the 2021 New Year to more than 5.5 million people. The broadcast also included videos from citizens and a conversation with JAXA astronaut Soichi Noguchi. The organization plans to continue this event annually, reaching millions more people with its 2022 New Year broadcast.

The project also helped connect people around the world, including the elderly, students, and families, during the isolation of COVID-19 lockdowns.

"This project not only created the opportunity to look up at the sky, but also provided a space to be together and see they share the same situation," said JAXA Space Innovation through Partnership and Co-Creation producer Shinichi Takata. "It's very symbolic. It was an event not only for the Japanese, but also people all over the world."

Illustration of future AVATAR X robots aboard the space station. Credit: avatarin Inc.

Students participate in a live education downlink with astronauts aboard the International Space Station. Credit: NASA

Those not able to participate in a live event can connect to the space station on demand through Story Time from Space, sponsored by the ISS National Lab. Astronauts record videos of themselves reading children's stories, which can be watched by anyone with internet access. Each video has amassed hundreds of thousands of views. The most popular, Auñón-Chancellor reading If I Were an Astronaut, has been viewed on YouTube over 600,000 times. The videos can be watched anytime and from home, providing an important resource for inspiring the next generation of explorers.

Just as research on the space station continues to innovate, so do outreach efforts.

One of JAXA-promoted private company's missions in Kibo is Avatar-X. This is a partnership project of JAXA and avatarin Inc. (a spin-out start-up company of ANA Holdings Inc. aiming to support the growing space-based economy by accelerating the development of real-world avatars), which plans to launch teleoperated robots that civilians can control from Earth. Similar avatar robots are already deployed in various facilities on Earth, enabling Japanese citizens and students to remotely explore facilities like JAXA centers and aquariums as if they were there in person. Next up is bringing the robots to space.

"One of our goals is to make space more relevant to everyday people," says Kevin Kajitani, chief operating officer of avatarin Inc, the developer of Avatar-X.

In 2020, a test conducted aboard the International Space Station allowed anyone that came by a booth in Tokyo to control a robotic camera installed in the space station in real time. Building on this success, the team is now working toward the launch and testing of more advanced robotic avatar systems aboard the station. These programs will pave the way for the next step in space outreach: the Moon.

"The future step is we want to actually place a robot on the Moon or Mars to allow children to virtually walk around and explore," said avatarin Inc. chief executive officer Akira Fukabori.

The ARISS program is also looking ahead and preparing to take advantage of future opportunities. They plan on installing a ham radio facility in Gateway, a vital component of NASA's Artemis program. The multipurpose outpost orbiting the Moon will provide essential support for long-term human return to the lunar surface and serve as a staging point for deep space exploration.

Conversations, story times, video, and other programs like these bring all of humanity along on the next stage of humankind's exploration of the cosmos.

Generation Station

ESA (European Space Agency) astronaut Thomas Pesquet poses for a photo next to AstroPi Raspberry Pi computers equipped with visual and infrared cameras. Credits: NASA/ESA

The International Space Station is inspiring the next generation of scientists

People born after November 2000 have always known life with humans in space: they grew up in a world with an International Space Station orbiting overhead. Call them Generation Station, those for whom space has always seemed accessible, a place where scientists from around the globe conduct research. Perhaps it is no wonder that many members of this generation have already sent their own research and hardware to the microgravity laboratory.

To help them continue to do so, many space agencies offer challenges and programs for students in their countries to send experiments into orbit.

"The space station really provides a unique environment for students to be able to have tangible access to space," said Alana Bartolini, ISS and international education operations coordinator at Telespazio Belgium SRL for ESA (European Space Agency). "They are not just doing a simulation. They are designing a real experiment and sending it to space."

For the European Astro Pi Challenge, students send code directly to station. Two levels of challenge enable younger students to measure humidity and display a personalized message to the astronauts while older students conduct full experiments that can yield meaningful scientific benefits. Over 15,000 students ran code via the Astro Pi Challenges on the space station from 2020-2021.

"The kids are really creative and imaginative. They do not just stop at 'here is the sensor reading, this means that the temperature is this'. They take it further, using critical thinking to explore what that value could mean in larger context," says Bartolini.

One of the Astro Pi Challenge experiments tested whether astronauts can be detected in a station module without using visual indicators.

"The students found out how to detect the crew without us telling them," said Aurora Technology B.V. for ESA STEM Didactics Expert Elsa Sanchez. "The first way was by measuring humidity inside the Columbus module.

Winners of the 2nd Kibo Robot Programming Challenge (from left to right) Settapun Laoaree, Kornpapop Sittirit, and Tarit Witworrasakul pose for a photo. Credit: Assumption College Thonburi

When someone was close to the Astro Pi, they emitted water vapor and humidity levels would rise, indicating that an astronaut could be nearby."

Other space agencies also run code challenges for students in space. JAXA has hosted a robot coding project in space called the Kibo Robot Programming Challenge (Kibo-RPC) since 2020, open for any age in the Asia-Pacific region.

"By having students compete as a team, it makes it more inviting and cultivates students' leadership, teamwork, perseverance, and creativity," said Yayoi Miyagawa, associate senior administrator of JAXA. "The students do not need any equipment except computer and Wi-Fi. They can participate in their home country wherever they are."

This challenge invites Asian students to first run their code in a simulation. Those who succeed move on to the next round, and their code is used in space to control NASA's Astrobee, a free-flying robotic system aboard the orbiting lab.

"Some of the students have never used the coding language Java before, and their first time was during this challenge. The leaders of the winning teams in 2021 and 2020 told me they had never learned Java before. Yet, they study hard to build the code and run the simulators to see how it works over and over. Through their continuous efforts, they were able to win the game," said Miyagawa.

That team leader in 2021 was Thailand-based student Tarit Witworrasakul. He led a team, Indentation Error, to victory as a high school student, even beating out university teams for the win.

"Participating in this program made me even more confident that I made the right decision to study STEM. Besides being very challenging, I think this field is also fun, stimulating, eye-opening, and very rewarding when you see the results in the end," said Witworrasakul.

NASA's High school students United with NASA to Create Hardware (HUNCH) program gives students the opportunity to participate in the design and fabrication of real-world products for NASA.

HUNCH started in 2003 with two schools in Alabama and one in Texas. Now, over 250 schools in more than

NASA astronaut Megan McArthur poses with the Astrobee robotic free-flyers in support of the Robo-Pro Challenge, which allows students to create programs to control Astrobee, a free-flying robot aboard the International Space Station. Credit: NASA

Genes in Space-6 team Aarthi Vijayakumar, Michelle Sung, mentor Deniz Atabay, David Li, and Rebecca Li outside the NASA vehicle assembly building at Kennedy Space Center. Credit: Genes in Space

40 states participate in six focus areas: design and prototyping, software, hardware, sewn flight articles, video, and media and culinary arts.

Students from Cypress Ranch High School, Cypress, Texas, present mock-up hardware to staff at NASA's Johnson Space Center. This hardware was built for NASA training programs as part of the HUNCH program. Credit: NASA

The program has produced more than 1,500 items for flight or training for the space station program, representing approximately 20,000 individual flight parts. That includes the creation of four storage lockers flown on NASA's Demo-2 mission and a new tape dispenser for use in space.

Additionally, a contest sponsored by the ISS National Lab, Genes in Space, challenges students in grades 7 through 12 to design DNA analysis experiments using tools aboard the station. Winning proposals are developed into research projects launched to the space station.

The 2018 winning proposal came from a group of students from Minnesota: Aarthi Vijayakumar, Michelle Sung, Rebecca Li, and David Li. Their project created double-strand breaks in yeast DNA, allowed cells to repair the breaks, and examined the repairs for mutations. The experiment marked several historic milestones: the entire process took place on the space station, and it used CRISPR-Cas9 technology in space for the first time.

The four students had conducted lab-based research during summers in high school and were looking for science competitions to enter.

"We knew astronauts have increased risk of cancer and wanted to figure out why," said Vijayakumar. They examined previous studies and saw that many focused on DNA break repair, which had not been studied in space.

"We decided to do the complete workflow in space to isolate the process and get a more thorough picture, without bringing samples back down where gravity could have affected the DNA repair," she said. The students worked with scientists at NASA, aerospace company Boeing, and biotech company miniPCR to prepare the experiment for space.

Vijayakumar is now a student at Yale studying molecular biochemistry and biophysics, a path inspired in part by her Genes in Space experience.

"It was really out there compared to anything we'd done before," she says. "Space biology is different from a lab on Earth; there are things you have to consider that never show up here. Learning how to create an experiment for the space station and watching the professionals was just as informative to us as the actual science itself."

Astronaut Kate Rubins wearing the COURAGE spacesuit comprised of artwork from pediatric cancer patients. Credit: NASA

Launching Art to New Heights

At the intersection of space exploration and creativity, the space station is a unique platform for artistic expression. Projects spanning multiple media, from the visual arts to music, have inspired audiences from hundreds of miles above.

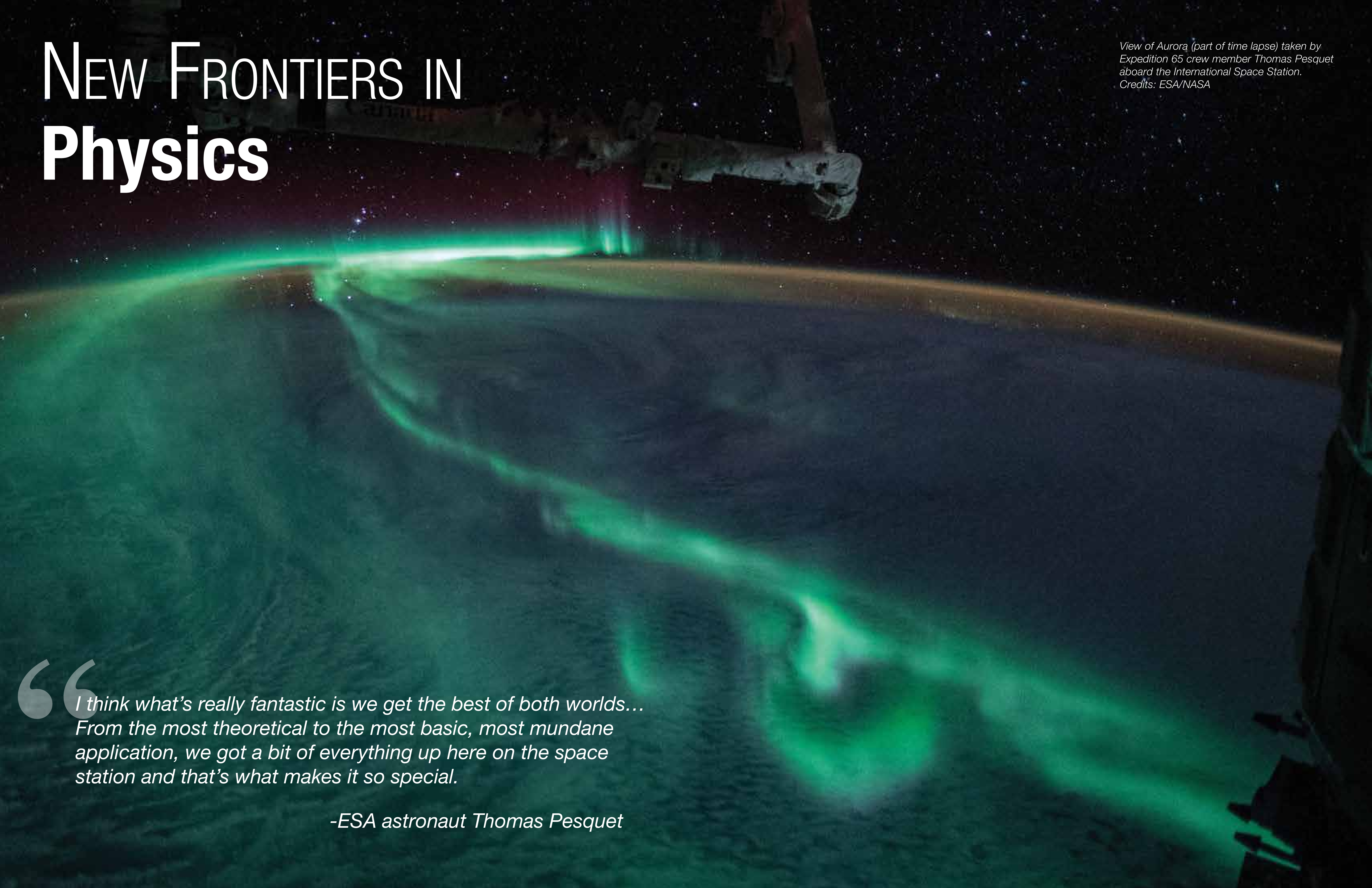
As part of a program to help patients cope with their cancer treatments through art, the Spacesuit Art Project invited over 530 pediatric cancer patients at MD Anderson Cancer Center, family members, and support personnel to paint canvas strips. The hand-painted art pieces were stitched together and incorporated into three spacesuits that were fittingly named HOPE, COURAGE, and UNITY. The COURAGE suit, created solely by pediatric patients, was launched to the station and worn by cancer researcher and NASA astronaut Kate Rubins. She provided special downlinks to speak with the patients and to raise awareness for childhood cancer research.

The MIT Media Lab Space Exploration Initiative also made an "open call" to artists around the world to participate in the Earthlings experiment. Art samples were deployed in a rotating structure aboard the space station. The project empowered a new generation of artists, designers, and creatives to engage their art in extreme and remote environments, which in turn inspires people on Earth.

Inspiring audiences in a different manner, ESA (European Space Agency) astronaut Luca Parmitano in 2019 became the first DJ in space. He broadcasted a live 12-minute DJ set from the International Space Station for concertgoers on the Spanish island of Ibiza." While energizing the crowd, the project was intended to inspire younger audiences about ESA and space exploration.

During "Paint with the Astronauts" day at MD Anderson Cancer Center, a patient poses with NASA astronauts Nicole Stott (left) and Reid Wiseman (right). Not shown: NASA astronaut Ellen Baker. Credit: NASA/Lauren Harnett

New Frontiers in Physics



View of Aurora (part of time lapse) taken by Expedition 65 crew member Thomas Pesquet aboard the International Space Station. Credits: ESA/NASA

> *I think what's really fantastic is we get the best of both worlds… From the most theoretical to the most basic, most mundane application, we got a bit of everything up here on the space station and that's what makes it so special.*
>
> *-ESA astronaut Thomas Pesquet*

ESA (European Space Agency) astronaut Samantha Cristoforetti - dressed in a Star Trek Voyager uniform - takes a sip of espresso from the new Capillary Beverage investigation, also known as Space Cup, while looking out of the station's cupola window. Credit: NASA

Going with the Fluid Flow

Studying fluids in microgravity is improving consumer products like shampoo and advancing technologies like life support systems

The fog of gravity is present in every experiment performed on Earth, clouding those observations and limiting our understanding. Heading to the International Space Station removes that fog.

Microgravity allows researchers to study the physics of our universe, from the properties of metals to atoms, through a completely new lens. Research on the space station is revealing fundamental science that can change our lives on Earth.

"Being in microgravity, you are in an environment where you can remove gravity. So, some processes that are masked on Earth you can study in this environment," says ESA (European Space Agency) scientist Marco Braibanti.

Colloids are mixtures of tiny particles suspended in a liquid. They include natural mixtures such as milk and muddy water as well as a range of manufactured products from shampoo to medicine to salad dressing. Studying colloids is complicated by the fact that gravity causes some particles to rise and others to sink. Microgravity removes that complication and makes possible research like the Advanced Colloids Experiments (ACE) conducted by NASA, the International Space Station (ISS) National Laboratory, and Procter & Gamble (P&G). This series of studies helps companies design better products used in our everyday lives and could inform the creation of entirely new ones, including some that could enable exploration farther into space.

The latest formulation of P&G's Febreze Unstopables TOUCH Fabric Spray with touch-activated scent release technology is the first to incorporate materials based on this colloids research.

"It's an amazing fluid that looks and feels like water," says P&G researcher Matthew Lynch.

"The work on the station helped us envision and understand the formulation."

ESA (European Space Agency) scientist Sébastien Vincent-Bonnieu (left) performing zero-gravity foam experiments on a parabolic flight where short-term microgravity can be used to prepare and test experiments for the space station. Credit: ESA

Lynch says some two-thirds of P&G's biggest brands could benefit from colloids research and in turn improve products for consumers. Space station research has contributed to three new patents for the company. Lynch points out that even a 1% savings in production costs or a slightly longer shelf life for household staples such as Downy fabric softener becomes significant. P&G products are used by an estimated 4.8 billion people every day—more than half of Earth's population.

"The success of the P&G spaceflight experiments is more than just a compelling business impact," Lynch said. "More importantly, what we learn here is going to help a lot of people."

Other companies, including Delta Faucet, also have taken advantage of station physics research to improve their products. Their Droplet Formation experiment in collaboration with the ISS National Laboratory used microgravity to evaluate water drop formation and water flow from Delta Faucet's H2Okinetic showerhead to create better performance, improve user experience, and conserve water and energy.

ESA also performed numerous microgravity fluids studies, contributing greatly to our understanding of boiling, heat transfer, and fluid flows. The FOAM experiment studied bubble size, rearrangement dynamics, and other properties of wet foams. Foams break down quickly in gravity, making them difficult to study on Earth.

"On Earth, liquid drains. That masks some other effects like coarsening, which is when gas passes between foam bubbles," says Braibanti.

Solid and liquid foams are used across a variety of industries, from cleaning products to food and medicines. Gaining a better fundamental understanding of foams could help improve their control and process design in these industries.

NASA astronaut Shannon Walker sets up Packed Bed Reactor Experiment (PBRE) hardware components. The PBRE study explores how liquids and gases behave together in a filtration packing material in microgravity, which may enable the design of more efficient, lightweight water recovery life support systems that use less energy on future space exploration missions. Credit: NASA

"We can learn something new doing experiments that nobody has done before in a unique environment. You learn new things that you can then apply in novel applications on Earth and in space," says Braibanti.

The ESA RUBI experiment analyzed a very different type of bubbles: those formed during boiling. Without gravity, boiling takes place in slow motion and produces larger bubbles. RUBI allows scientists to observe and measure effects that are too fast and too small on Earth, getting a more complete understanding of heat transfer during the boiling process. This information could be applied to help cool electronics such as laptops more efficiently.

"Scientists are in the process of analyzing all of RUBI's data. Then we are planning to launch a new facility called Heat Transfer Host that hosts a number of different experiments in the field of heat transfer. The idea is to use the results that we have from RUBI in the design of the new experiments," says ESA scientist Sebastien Vincent-Bonnieu.

The changes that microgravity causes in fluid behavior also can present challenges for transitioning Earth technologies to space.

"We test reactor beds extensively on the ground, then fly the same thing and it underperforms in space," said Packed Bed Reactor Experiment (PBRE) principal investigator Brian Motil of NASA's Glenn Research Center in Cleveland, Ohio.

Reactors are critical to space exploration: they are used to reclaim and purify water, clean air, and provide many of the life-sustaining processes we take for granted on Earth. Because of the gap in our knowledge about how two-phase (i.e., between a gas and liquid, or between a liquid and solid) systems work in microgravity, reactor designers do not have the necessary tools to create more-efficient systems.

NASA astronaut Kate Rubins works on the SODI DCMix-3 installation inside the station's Microgravity Science Glovebox. Credit: NASA

And as we travel farther into space, reactor efficiency must improve.

"The pressure drop in reactors in space is different than we expected," said Motil. "Because of that, our focus has been to answer those fundamental questions of what is going on and what is the minimum flow rate we need to flush bubbles out of the system."

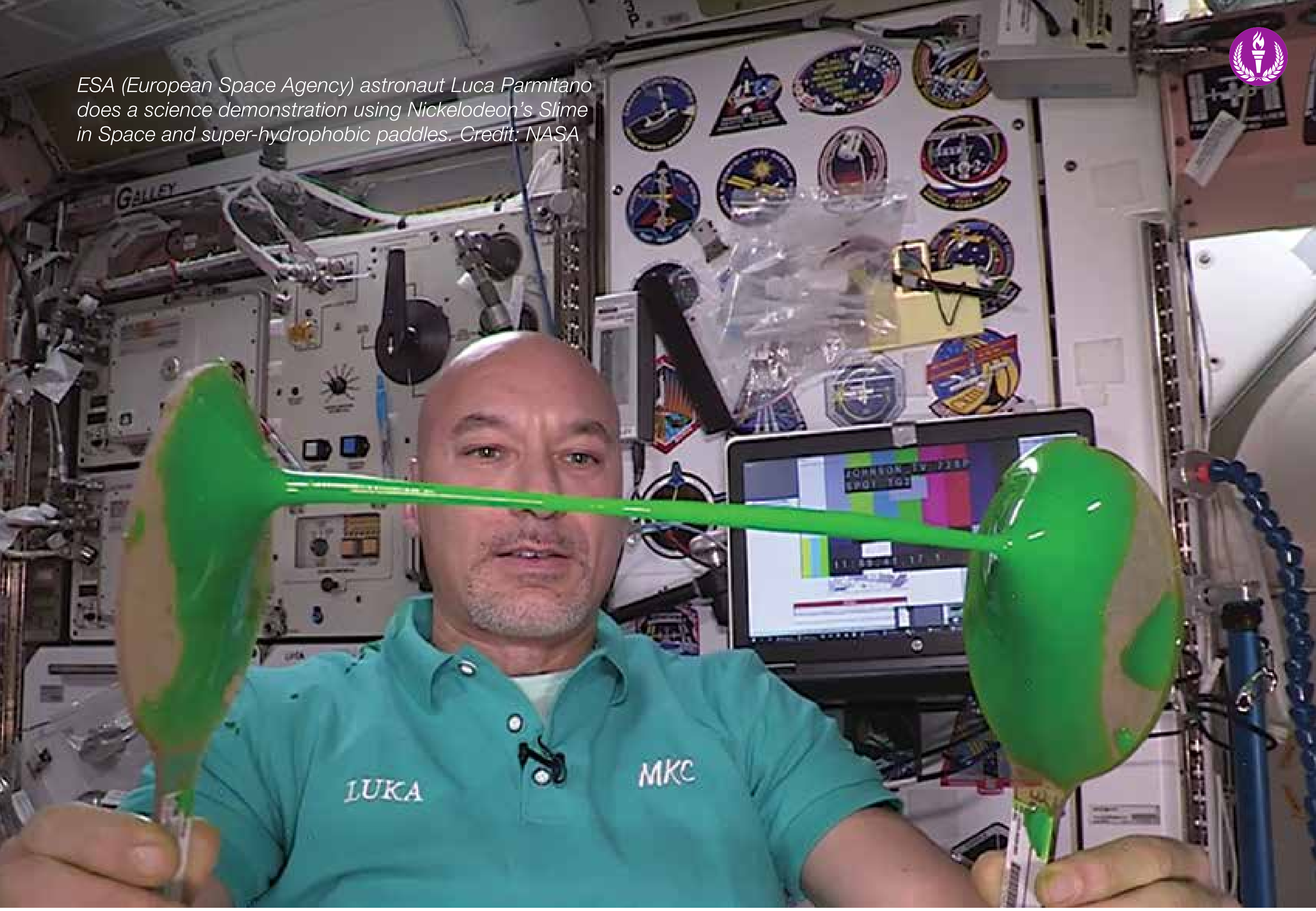
The space station provides a tool for understanding this drop of performance and could enable scientists to increase the efficiency of life support systems.

"This research will enable us to do long-duration spaceflights, ones where astronauts will have to recycle most of their resources. Reactor beds are one of the many technologies that really need to be well-tested prior to going to Mars," said Motil. "Without the space station, we have no platform to validate what we have developed."

Pressure-drop calculations generated by the PBRE team so far already have been successfully applied to other station experiments at high flow rates. The IVGEN study, which tested the ability to generate water of sufficient quality for intravenous use in microgravity for medical emergencies, used these calculations to flush their system before the experiment. But high flow rates can damage reactor bed material, so research continues to conquer the low flow rate question.

Other space station fluids experiments also are providing actionable information and results. The ESA SODI-DCMIX study calculated how much certain mixtures of fluids and gas molecules move and collide, which could help us better understand the behaviors of these chemicals in underground oil reservoirs. Studies of capillary forces, the small pushes and pulls that move liquid through a narrow tube, have led to the development of a special cup that can be used in space, and the testing of new life support systems that rely on shapes and fluid dynamics rather than complex pumps to move and store liquid.

"We have shown to the scientific community this can work and deliver interesting results," said Vincent-Bonnieu. "And now that we are delivering a number of results, we are actually seeing growing interest in space station research. We are opening more doors than we are closing."



ESA (European Space Agency) astronaut Luca Parmitano does a science demonstration using Nickelodeon's Slime in Space and super-hydrophobic paddles. Credit: NASA

Physics Research Gets Slimed

"The data can be applied to work around low-gravity droplet production, mitigation, and containment and help inform continued work concerning general liquid containment, hydroponic plant watering in space, and more.

Who knew green goo could be both educational and scientific! U.S.-based television channel Nickelodeon worked with the International Space Station National Laboratory and researchers behind station fluids studies to send slime to space. The investigation Nickelodeon Slime in Space served both as research on non-Newtonian fluids and an outreach effort.
The final product taught viewers about microgravity and materials science principles in a fun and engaging 15-minute virtual field trip targeted at grades 3-5. The field trip has been already viewed more than 600,000 times.

Sending this large amount of highly viscous liquid to the space station was a unique opportunity for fluids researchers. Scientists recorded observations of the slime's fluid properties using eight demonstrations. These simple demonstrations provide valuable data on liquid behavior in microgravity. Such data inform the analysis and design of new space technology and space-based research. The data can be applied to work around low-gravity droplet production, mitigation, and containment and help inform continued work concerning general liquid containment, hydroponic plant watering in space, and more.

And of course, it is also fun to see astronauts slimed in space.

View of the Neutron star Interior Composition Explorer (NICER) payload mounted on the International Space Station. NICER's primary mission to perform an in-depth study of neutron stars offers unrivaled astrophysics knowledge and may revolutionize scientists' understanding of ultra-dense matter. Credit: NASA

Space Station Study of Neutron Stars Helps Improve CT Scans

Advances in X-ray technologies to create a space station telescope help us unravel the mysteries of our universe while potentially improving medical devices

When the team behind NASA's Neutron star Interior Composition Explorer (NICER) developed their astrophysics experiment for launch to the International Space Station, they faced unique challenges. Researchers needed to create new X-ray technologies to best study the glowing cinders left behind when massive stars explode as supernovae and form neutron stars. What the NICER scientists never expected was that the technologies they developed for overcoming these challenges in space could lead to new advances in medicine.

NICER team members apply epoxy to the X-ray concentrator mounts prior to launch. The epoxy held the optics assemblies fixed in position through the vibrations experienced during launch to the International Space Station. Credit: NASA

In 2017, NICER joined other astrophysics experiments such as the Japan Aerospace Exploration Agency's (JAXA's) CALET and MAXI, and NASA's AMS-02 in using the outside of the space station as a unique perch for studying the universe.

"We designed the mission to study neutron stars because they are really fantastic objects. They represent the densest matter that we know of in the universe. If you could squeeze a neutron star any further, it would implode into its event horizon and become a black hole," said Keith Gendreau, NICER principal investigator at NASA's Goddard Space Flight Center in Greenbelt, Maryland. "We do not know how matter behaves at these super-high densities because we cannot reproduce them in any experiment here on Earth or in the solar system."

NICER's observations of neutron stars have already led to numerous findings. In 2019, NICER detected a sudden spike of X-rays caused by a thermonuclear flash on the surface of a pulsar, a rapidly spinning neutron star. It also provided the first ever surface map of hot spots on a pulsar's surface in the same year. In 2021, the telescope helped scientists discover that matter in the heart of a neutron star is less squeezable than some physicists predicted, NICER's key science goal.

Scientists from around the globe are now using the payload to study everything from black holes to comets. For example, scientists used NICER to chart the environment surrounding J1820+070, a black hole about 10 times the Sun's mass. That discovery made the cover of the January 2019 issue of the scientific journal Nature.

But before NICER did any of this, the research team worked on the ground to figure out how the experiment could provide accurate time-tag measurements of X-rays.

"NICER's measurement capabilities that are unique involve timing. The instrument records to extremely high accuracy the time at which X-rays coming from the sky are received,"

This miniaturized X-ray source was used to test the NICER payload and is now being used for developing new CT scan technology. The high-speed switching capability and miniature size make possible many new technologies, including X-ray-based communication, novel X-ray fluorescence and diffraction instruments for materials science, low and precise dose medical X-rays, and more. Credits: NASA/Goddard/Samantha Kilgore

Gendreau said. "To verify that performance on the ground, we needed an X-ray generator that could produce X-rays at commanded times."

Traditional X-ray sources were limited in how quickly they could be turned on or off. The researchers needed to shorten that time from milliseconds to nanoseconds. To solve this challenge, the NICER team created and patented the Miniaturized High-Speed Modulated X-ray Source (MXS).

This also happened to be just what neuroradiologist Dr. Raj Gupta of Massachusetts General Hospital was looking for in his quest to improve computed tomography (CT) scans.

CT scans, formerly known as CAT scans, are obtained using rotating X-ray machines that image the body to provide important three-dimensional information to medical professionals. According to Harvard Health Publishing, more than 80 million CT scans are performed in the United States alone each year.

> "According to Harvard Health Publishing, more than 80 million CT scans are performed in the United States alone each year.

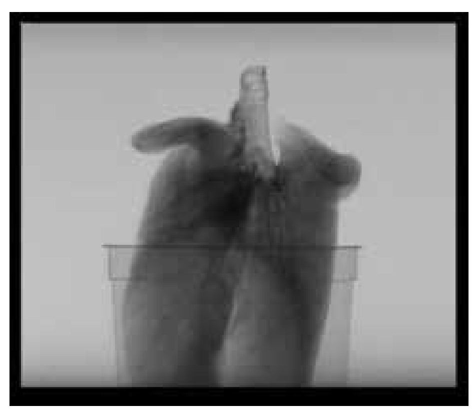
Traditional CT machines are large, heavy, and consume a lot of power, making them difficult to ship and hard to access in environments with few resources.

"Where I grew up, there is really no medical imaging. And even now there is very little penetration of advanced medical imaging there. Even simple X-rays are not available to about two-thirds of the world, according to the United Nations," Gupta said.

Gupta lived in the small village of Malsisar in northwest India until he was nine years old. His desire to make medical technologies more accessible drove Gupta's work to improve the devices. Coincidentally, what his research needed was similar to what the NICER team had created: a small, lightweight X-ray source that could turn on and off very quickly.

When Gupta attended a talk put on by Gendreau, also the lead inventor of MXS, Gupta knew that it was something special. He saw the potential to increase the accessibility of CT scans, lower the radiation doses these procedures deliver to medical patients, and create new medical devices with potential use for space exploration. He reached out to Gendreau and the collaboration began.

"I never thought that when looking at some pulsars and neutron stars, I would



An X-ray image of a pig lung obtained by Dr. Raj Gupta's research team testing out the new CT scan technology. Credit: Raj Gupta, Massachusetts General Hospital and Harvard Medical School

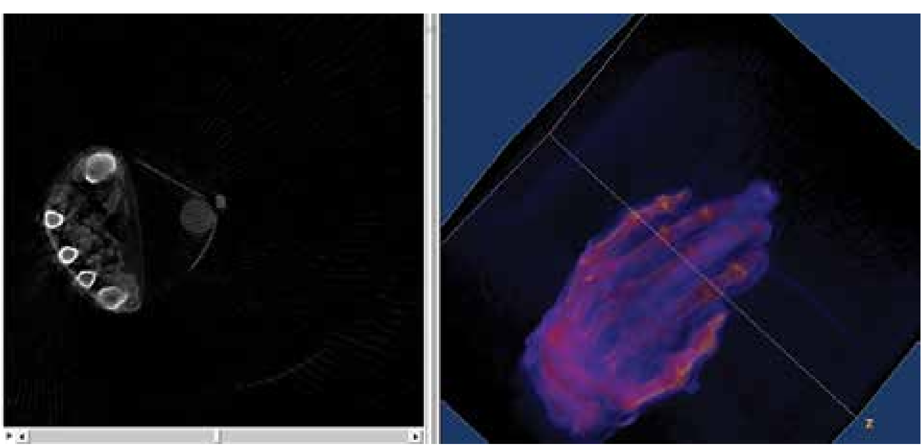
View of the experimental setup created by Dr. Raj Gupta's research team at Massachusetts General Hospital to image a pig lung to test the new CT scan method. The technology was developed using an X-ray source created for the NICER payload aboard the space station. Credit: Raj Gupta, Massachusetts General Hospital and Harvard Medical School

find some technology that will be useful in my day-to-day work," Gupta said.

Rather than spinning the large X-ray machine around to capture a CT scan, Gupta worked with the NICER team to create a stationary ring of these new, small, modulated X-ray sources that can be mounted around the patient, firing when needed.

"If you have many X-ray sources around a person, then you can turn on the ones that are giving the doctor more information more often and those that are giving less information less often," Gupta said.

This technique can decrease the amount of radiation the patient is exposed to and enable better image quality for that level of radiation. Limiting radiation exposure is helpful for patients on Earth now and for potential future astronauts on their way to Mars.



A scan of a human hand obtained by Dr. Raj Gupta's research team testing out the new CT scan technology. Credit: Raj Gupta, Massachusetts General Hospital and Harvard Medical School

"In space, because it is a high radiation environment to begin with, this is even more important," Gupta said. "Currently, long missions take months, if not years, to complete. In that time, somebody could get sick or injured. There may be physicians aboard who can actually do something about it, but the traditional CT scanner is just not placeable in a space environment."

Gupta and his team have already performed successful test scans on pig lungs and human hands. They published their initial results in Nature Scientific Reports in 2018. Their next step is to increase the size and power of the setup for full-scale human testing.

"What has happened to the accessibility of consumer electronics has not happened to medical imaging, and ideas like this move the ball in that direction," Gupta said.

He is hopeful that as more scientists from other fields study the work of NICER scientists, more medical benefits will arise.

"They have this method of taking X-rays and kind of concentrating them. They have essentially made a focusing system for X-rays that could be used in mammography," Gupta said.

While this progress continues in the lab on Earth, NICER will continue staring up at the skies.

"There are lots of intriguing aspects about what goes on physically inside neutron stars, including super conductivity and super fluidity – all these weird quantum phenomena that are almost science fiction except that they're not," said Zaven Arzoumanian, NICER deputy principal investigator at Goddard.

Superconductivity and superfluids can be created in the lab, but only in tiny quantities. Neutron stars offer the rare opportunity to study quantities of superfluid that weigh as much as the Sun.

"We are exploring quantum phenomena that are happening on enormous scales, and understanding them can have technological relevance to us," Arzoumanian said.

NICER's continued work analyzing neutron stars and helping us better understand our universe may in turn lead to new ways of helping us back on Earth.

Monitor of All-sky X-ray Image (MAXI) attached to the Japanese Experiment Module - Exposed Facility (JEF). Photo taken during STS-127/Expedition 20 Joint Operations. Credit: NASA

Automating an Astrophysics Collaboration That Bridges Countries and Galaxies

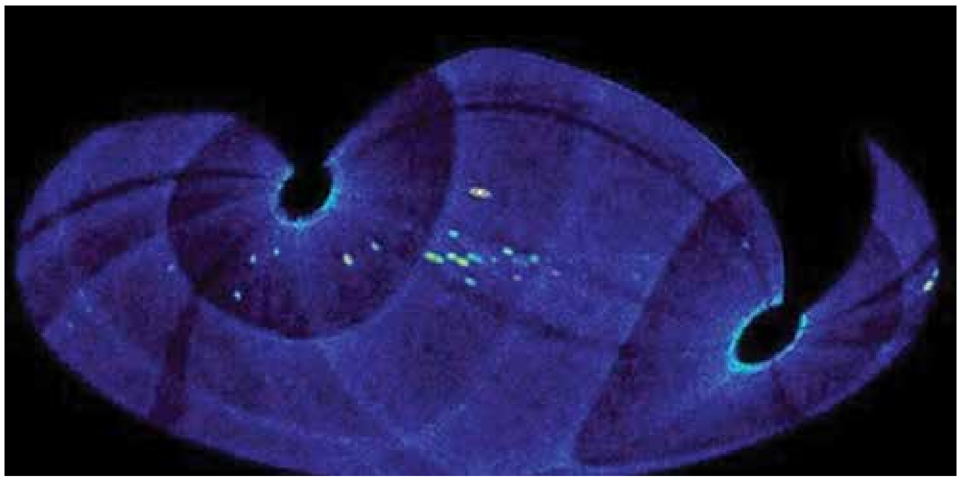
An international collaboration between NASA's NICER and the Japan Aerospace Exploration Agency's (JAXA's) space station experiment MAXI has jump-started the discovery of unpredictable cosmic events that reveal the workings of our dynamic universe. MAXI has scanned the skies for X-ray sources from the vantage point of the space station since 2009, alerting other observatories so they can capture additional data about these sources.

"The space station is in contact with a ground station about 70% of the time. We can get data from MAXI about 10 seconds after it detects something. Prompt analysis on ground computers makes it possible to issue an alert to observatories all over the world through the internet," said MAXI co-investigator Tatehiro Mihara.

The NICER team is one group receiving these alerts. While MAXI scans 95% of the X-ray sky with each orbit of the station, NICER measures a much smaller patch of sky with much higher sensitivity to faint objects. This makes the two instruments a perfect pair.

In one instance, astronomers were unaware of the presence of black hole J1820 until MAXI spotted an outburst on March 11, 2018. Outbursts occur when an instability in the disk causes a flood of gas to move inward, toward the black hole, like an avalanche. The causes of disk instabilities are poorly understood. J1820 went from a totally unknown black hole to one of the brightest sources in the X-ray sky over a few days. NICER moved quickly to capture this dramatic transition and followed the fading tail of the eruption over several months.

> "In one instance, astronomers were unaware of the presence of black hole J1820 until MAXI spotted an outburst on March 11, 2018.



The first all-sky X-ray image obtained with a camera on the Monitor of All-sky X-ray Image (MAXI) during one International Space Station orbit. Credit: Japan Aerospace Exploration Agency (JAXA).

However, vastly differing time zones between the United States and Japan do complicate this collaboration. The Orbiting High-energy Monitor Alert Network (OHMAN) project is taking on this challenge by automating the relationship between the two payloads.

"NICER and MAXI are both on the space station, so why go through the bother of sending information to the ground at all?" said Keith Gendreau, NICER principal investigator at NASA's Goddard Space Flight Center in Greenbelt, Maryland. "It should be possible for MAXI to do its automated analysis and determine whether something is worth NICER's attention. Then NICER can follow up on the X-ray source automatically, cutting the response time from hours or days to minutes."

A laptop aboard station connected to both instruments serves as the bridge between the two missions. By automating this notification process, NICER and MAXI can work more closely together than ever before, using X-rays to uncover more mysteries of the universe and advance scientific understanding – and hopefully something more.

"When MAXI sees X-rays in real time in the sky and informs humans for the first time, we see a new world where a star suddenly brightens up and black hole binaries twinkle in a millisecond," Mihara said. "It might just be beautiful to some people, but sometimes it inspires them."

Ya-Ting Liao, an investigator for the Confined Combustion experiment, discusses the investigation, which studies how fire spreads and behaves in confined spaces, during a What's On Board Briefing for SpaceX's 19th Commercial Resupply launch. Credit: NASA

You're Hot Then You're Cold

Extreme temperatures aboard the space station are helping us uncover new information about our universe, keep people safe from fires, and more

Physics research requires extremes. The International Space Station delivers those extremes, from generating some of the coldest temperatures in the universe to using hot flames and furnaces to heat samples above 2,000°C (3,632°F). Keeping things cold can slow down processes in unique ways in microgravity while understanding how fire spreads and behaves in space is crucial for the safety of astronauts in space and advances our knowledge of combustion and fire control on Earth.

Let us go to the extremes and push the boundary of what we know for the sake of science and safety here on Earth.

You're Hot

Fuel efficiency and reducing pollution

"Most of our electricity in the United States is generated by combustion," says NASA's Glenn Research Center project scientist Dennis Stocker. "In regard to powering cars, where would we be without combustion? Combustion is a big part of our modern lives."

The International Space Station helps combustion researchers test core principles of their field, removing the variable of gravity, which clouds flame experiments on Earth. The six Advanced Combustion via Microgravity Experiments (ACME) conducted in the Combustion Integrated Rack could yield data that help improve fuel efficiency and reduce pollutant production in combustion on Earth.

Discovering cool flames

"One of the biggest discoveries, not only in the microgravity program but in probably the past 20 to 30 years of combustion research, came during the FLEX experiments on the space station," says Glenn scientist Daniel Dietrich. When researchers on the FLEX study analyzed fire suppressants by studying burning fuel droplets, they made a surprising discovery: continued, low-temperature "burning" after apparent flame extinction.

Now known as cool flames, this combustion process is distinct from the flames that keep us warm by the campfire. Typical flames produce soot, carbon dioxide, and water. Cool flames produce carbon monoxide and formaldehyde. Learning more about the behavior of these chemically different flames could lead to the development of more-efficient, less-polluting vehicles.

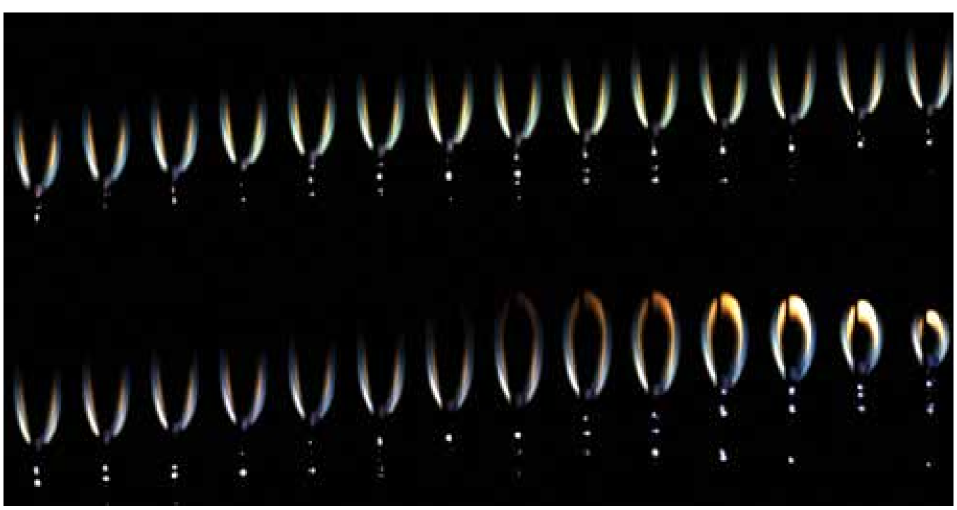
Since their discovery in 2012, cool flames have been produced on Earth, but they quickly flicker out. On station, cool flames can burn for minutes, giving scientists a better opportunity to study them.

"It's not only important from a nerdy theoretical combustion point of view, but also from a practical point of view," says Dietrich. "The low-temperature chemical reactions that we can study on facilities like the space station are very important in real combustion systems like engines."

Flames in tight spaces

Confined Combustion could help keep us safer by improving fire safety codes. The spread of flames in confined spaces such as buildings and vehicles may pose a more serious fire hazard than flame spread in open spaces because of heat radiating back from the surrounding walls. This experiment studied fire movement through differently shaped spaces in microgravity to give us a better understanding of how fire behaves in these areas on Earth.

"It felt unreal that this project, so close to my heart, was in space 200 miles above my head," says principal investigator Ya-Ting Liao. Liao's lab is disseminating its findings among industry partners and the academic community to contribute to improving fire safety on Earth and in space. "We have a responsibility to use this unique experiment opportunity to impact science and life on Earth and beyond."



These flames were formed as a part of the Confined Combustion experiment aboard the space station when NASA astronaut Christina Koch conducted the first burn of the study on Christmas Eve 2019. Understanding how fire spreads and behaves in space is crucial for the safety of future astronauts and for understanding and controlling fire here on Earth. Credit: NASA

Understanding hot metals

To produce glass or metal alloys on Earth, raw materials are placed into a container called a crucible and heated. But reactions can occur between the crucible and the materials inside, causing imperfections. JAXA's Electrostatic Levitation Furnace (ELF) takes advantage of microgravity to study and process these hot materials without containers.

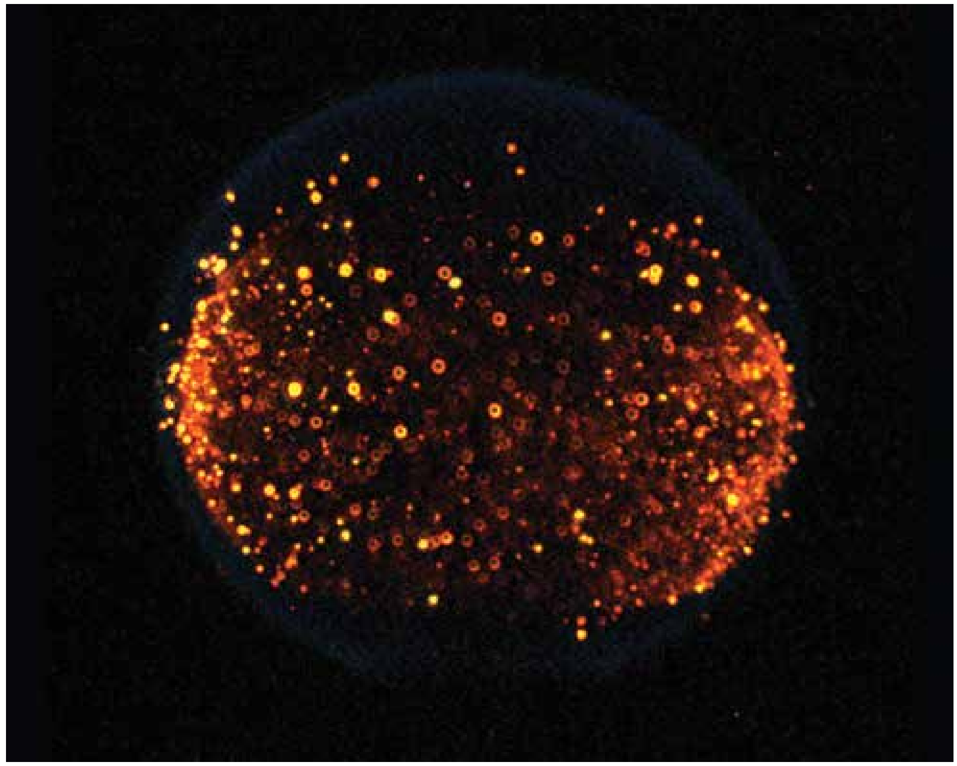
Every material has a very small electrostatic charge on its surface. ELF applies a high voltage to the sample, then levitates it using coulomb force, which forms from the attraction or repulsion of objects based on their electric charges. The amount of charge depends on the material's characteristics. If the electrostatic charge is very small, scientists cannot levitate the sample on Earth because coulomb force cannot overcome gravity. In microgravity, ELF can levitate almost all samples that cannot be levitated on the ground, providing insights into the properties of high-temperature metals and new types of materials.

"It is very difficult to control the samples in the right position in a super high temperature range above 1,000 degrees Celsius, because every material has its own characteristics. We do not know these characteristics on the ground, so there is a lot of trial and error in the space experiment," says JAXA scientist Hirohisa Oda. "When we successfully melt the new sample in space, it is a very happy moment for ELF team."

Oda says ELF may accelerate development of innovative material like super-diffractive index glass and super-high-heat resistant ceramics. These materials could be useful in aerospace and energy industries.

Predicting rocket engine behavior

Rocket engines widely use spray combustion of liquid propellants immediately after injection into the combustion chamber. The fuel and oxidizer move through the combustion chamber at high speeds, making analysis of the droplet and flame interactions virtually impossible. Group Combustion, the first combustion experiment performed onboard the Japanese Kibo module, could help improve numerical simulations used to predict spray combustion behavior in the development of these advanced rocket engines.



This flame was one of many ignited as part of the Flame Design investigation inside of Combustion Integration Rack to investigate the amount of soot that is produced in different conditions. The yellow spots are soot clusters that glow yellow when hot. These clusters grow larger in microgravity than on Earth because the soot remains within the flame longer. Credit: NASA

Putting out fires

We didn't start the fire – but we sure need to put it out. The Burning and Suppression of Solids (BASS) investigation examines how to extinguish a variety of fuels burning in microgravity. With adequate ventilation, materials may burn as well in microgravity as in normal gravity; however, putting out fires in space must consider the geometry of the flame and characteristics of the extinguisher. Otherwise, some ground-based type efforts may be ineffective or make the flame worse through increased interaction with oxygen.

BASS investigation results guide strategies for extinguishing accidental fires in microgravity and contribute to better fire detection and suppression systems on Earth.

Going big

The Saffire experiments are conducted aboard uncrewed Cygnus cargo spacecraft after they detach from the station. This squeezes in one extra dose of science to these missions, taking advantage of every opportunity to do research in microgravity. The distance from station enables tests of larger fires using instruments to measure flame growth, oxygen use, and more. This work improves our understanding of fire growth in microgravity, safe-guarding future space missions.

Then You're Cold

Going to the coldest place in the universe to advance quantum science

In July 2018, NASA's Cold Atom Lab (CAL) became the first facility to produce a new state of matter, called a Bose-Einstein condensate (BEC), in Earth orbit. A fundamental physics facility aboard the space station, CAL cools atoms to ultracold temperatures to study their quantum properties in ways not possible on Earth.

"With Cold Atom Lab, we're looking for new physics that pops up only when you can study the universe at extremely fine scales," said Jason Williams, the lead scientist for the Cold Atom Lab atom interferometer at NASA's Jet Propulsion Laboratory (JPL) in Southern California.

NASA astronaut Christina Koch handles science hardware stowed inside a cargo transfer bag retrieved from the SpaceX Dragon resupply ship. The hardware is part of the Cold Atom Laboratory that produces clouds of atoms that are chilled to about one ten billionth of a degree above absolute zero -- much colder than the average temperature of deep space. Credit: NASA

Chilling atoms is the only way to produce a BEC. The colder the atoms are, the slower they move and, following the rules of quantum mechanics, the larger and more wave-like they become. Ultracold atom facilities like CAL cool atoms to within a few billionths of a degree above the temperature at which they would theoretically stop moving entirely. Facilities in space can potentially reach colder temperatures than Earthbound labs because less energy is required to keep the atoms in place in space.

Longer observing times and colder temperatures both provide opportunities for deeper insights into the behaviors of atoms and BECs.

BECs serve as a valuable tool for quantum physicists because all the atoms in a BEC have the same quantum identity. This means they collectively exhibit properties that are typically displayed only by individual atoms or subatomic particles. BECs make those microscopic characteristics visible at a macroscopic scale.

“Even dating back to when the first Bose-Einstein condensates were made, physicists recognized how working in space could provide big advantages in studying these quantum systems,” said David Aveline, a member of the Cold Atom Lab science team at JPL. “There have been some focused demonstrations in this regard, but now with the continuous operation of Cold Atom Lab, we’re showing there’s a lot to gain by doing these prolonged experiments day after day in orbit.”

Quantum science touches our lives each day. Quantum mechanics refers to the branch of physics that focuses on the behaviors of atoms and subatomic particles. It is a foundational part of many components in many modern technologies, including cell phones and computers, that employ the wave nature of electrons in silicon.

Although the first quantum phenomena were observed more than a century ago, scientists continue to learn about this realm of our universe.

Cold Atom Lab now has run successfully for more than four years, and astronauts even helped upgrade the facility with a new tool, called an atom interferometer, that uses atoms to precisely measure forces, including gravity. The new instrument is working as expected, making it the first atom interferometer to operate in space.

Growing the Low-Earth Orbit Economy

NASA’s SpaceX Crew-4 astronauts participate in a training session at SpaceX headquarters in Hawthorne, CA. From left to right: NASA astronaut and SpaceX Crew-4 mission specialist Jessica Watkins; NASA astronaut and SpaceX Crew-4 pilot Robert “Bob” Hines; NASA astronaut and SpaceX Crew-4 commander Kjell Lindgren; and ESA (European Space Agency) astronaut and Crew-4 mission specialist Samantha Cristoforetti of Italy. Credit: SpaceX

> “*From the space agencies that started the International Space Station program, to now also having more and more commercial partners in there, shows to me that we are on the correct path.*
>
> *-ESA astronaut Matthias Maurer*

NASA astronaut Mark Vande Hei works on the Multi-use Variable-g Platform (MVP), a space biology research platform housing samples such as fruit flies, flatworms, plants, fish, cells, and protein crystals and can produce up to 2g of artificial gravity. Credit: NASA

Space Station Enables Launch, Growth of Space Businesses

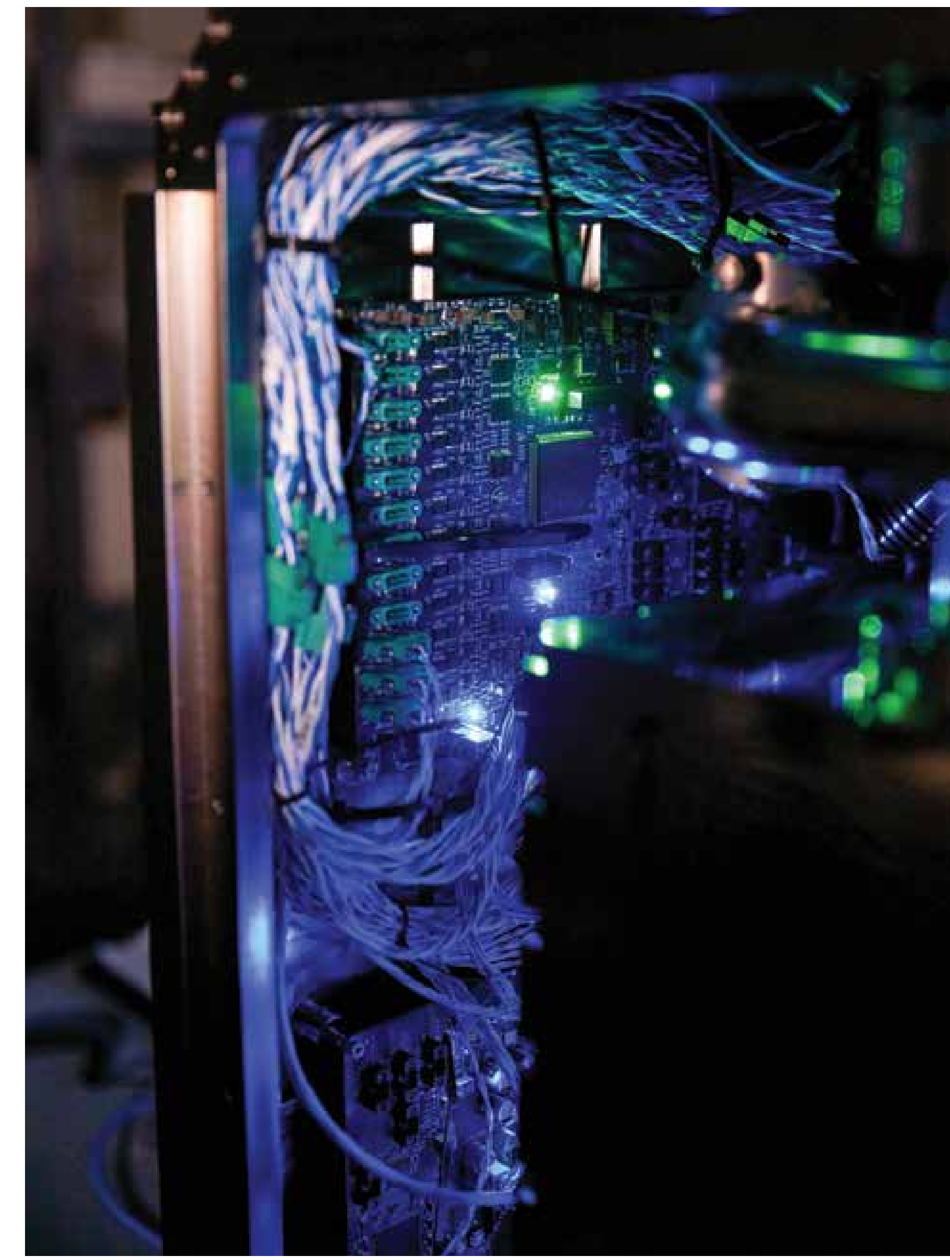
Leveraging space station technology platforms for economic benefit on the ground

The International Space Station provides platforms for small businesses, entrepreneurs, and researchers to test their science and technology in space. Not only has the station's capacity for research, development, and manufacturing in low-Earth orbit increased, the cost continues to fall. Together, these factors are advancing development of new and improved products as well as spawning new commercial ventures and providing growth for existing ones.

"We are walking through the door to the second golden age of space and seeing the beginnings of a growth surge in space-based businesses," says Andrew Rush, president and chief operating officer of Redwire Space. "In many ways, the space station has been responsible for opening that door. NASA's support of the development and demonstration of new technology and new uses of space has enabled entirely new sectors – in-space manufacturing and commercial research and development among them – to move forward."

The space station is helping to fuel growth of the space industry as a whole.

In the past several years, Redwire has acquired Made in Space and Techshot, companies focused on in-space manufacturing and space research, thus becoming one of the major players in this burgeoning economy. Its facilities include the station's BioFabrication Facility (BFF) and ADvanced Space Experiment Processor-2 (ADSEP-2), which support in-house efforts to create a complete set of cardiac tissues, and the Multi-use Variable-g Platform (MVP), which produces varying levels of artificial gravity for research on different diseases. In addition, the company has its own plant growth facility and manages research in the space station's Advanced Plant Habitat.



Turbine Superalloy Casting Module tests in-space manufacturing of superalloy parts in microgravity for terrestrial use. Credit: Redwire

Another Redwire focus has been using microgravity to create better turbine parts. The Turbine Ceramic Manufacturing Module (Turbine CMM) demonstrates manufacturing a type of turbine blade called a blisk, whereas Turbine Superalloy Casting Module (Turbine SCM) tests a manufacturing device that processes heat-resistant alloy parts in microgravity. Manufacturing in microgravity could allow production of these components with lower mass and stress. The parts show increased strength compared to those made on Earth. That increased strength could improve the performance of turbine engines in industries such as aerospace and power generation.

“The space station is pivotal to businesses developing space-based products and services because it provides rapid access to space and return capability,” says Rush. “The unique environment of the space station has been invaluable to Redwire’s development of in-space manufacturing technology and capabilities. It is the only cost-effective, accessible, and rapid platform to develop, test, and operate technologies that are revolutionizing so many critical areas for the benefit of humanity.”

Capitalizing on this growing space economy has enabled the company to expand to more than 500 employees and eight facilities in the United States and internationally.

The Nanoracks Bishop airlock, shown here installed to the port side of the Tranquility module and still attached to the Canadarm2 robotic arm, increases the station’s capacity for private and public research and enables the release of larger satellites and the transfer of cargo inside and outside the station. Credit: NASA

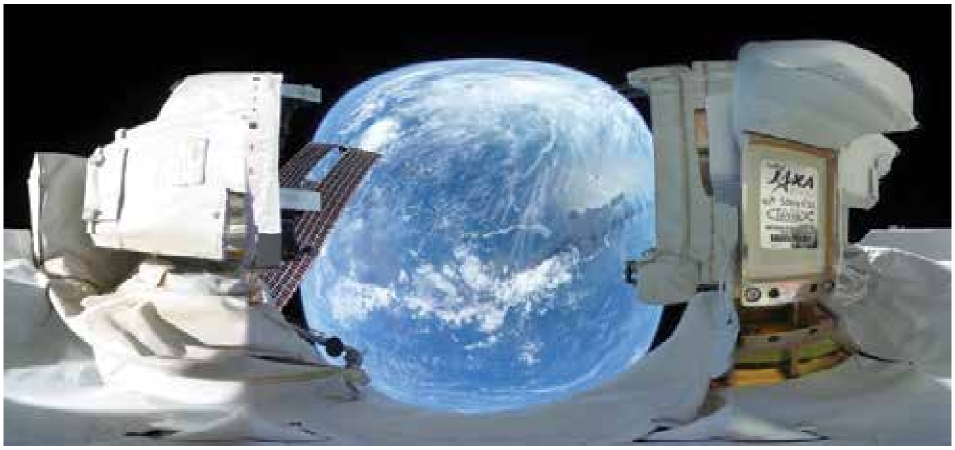
Houston-based Nanoracks is another company built largely on space technology. It has developed a multipurpose platform used on station for research on plant growth, radiation exposure, and materials and physical sciences. The company took a big step forward in 2020 with the launch of the Bishop Airlock, the station’s first commercially owned and operated airlock. The airlock adds a variety of capabilities, including deployment of small satellites called CubeSats and other external payloads and support for small exterior and internal payloads. It is much larger than the existing research airlock and therefore can accommodate more and larger payloads.

Another commercial provider, Space Tango, has an automated, reconfigurable research and development (R&D) and manufacturing platform called TangoLabs. This platform facilitates plant and agricultural science, organoid observation and growth, and flow chemistry, according to communications manager Danielle Rosales.

“The space station is currently the only in-space platform for microgravity R&D,” says Rosales. “We cannot do it anywhere else. It is a necessary incubator as we continue to identify the best pathways to manufacture health and technology products in space.” It also provides a pathway for Space Tango to grow as a company.

Another area of space research with commercial potential is the development of high-tech fabrics. The first scientific test of commercial fabrics on the space station was the ESA (European Space

This image shows CubeLabs installed in Space Tango’s TangoLab facility, which provides a standardized platform and open architecture for these experimental modules for use in 3D tissue and cell cultures. Credit: NASA



A high-definition image transmitted by SOLISS via laser communication. Credit: JAXA

Agency) SpaceTex-2 investigation, which tested fabrics that provide higher evaporative heat loss compared to conventional cotton fabrics. The fabrics, provided by Swiss performance fabric manufacturer Schoeller Textil AG, are a first step toward developing products for use in space. On Earth, warm, humid environments promote growth of bacterial, viral, and fungal skin infections and rashes, and these faster-drying textiles could help reduce these problems. Quick-drying clothing could help athletes, firefighters, and the military.

Several commercial entities even have plans for developing their own space stations. A first step in that direction is a module, developed by Axiom, that attaches to the space station, nearly doubling its useable volume. Axiom also is launching private astronaut missions, which are privately funded, fully commercial flights to the space station, on commercial launch vehicles. They are dedicated to outreach, commercial research, or approved commercial and marketing activities.

“There always will be applied and fundamental research that NASA and other agencies want to do that need a microgravity platform,” says Mike Read, manager of NASA’s space station business and economic development office. “But the International Space Station is going to be the last U.S.-government-led platform in low-Earth orbit. That is why we’re enabling the Axioms of the world to put a module on station and leverage its power, propulsion, and all of the space station infrastructure to build out their segment. Once it is built out, we can start thinking about separating the Axiom segment and comfortably retiring station.”

NASA has signed agreements with three other companies to develop space stations and other commercial space destinations: Blue Origin, Nanoracks, and Northrop Grumman Systems Corporation.

“Once these other platforms are up there, we can move facilities and customers into them to take advantage of that volume,” Read adds. “If we are going to develop the demand, we need a place to put it. We can provide scalability to some degree on the space station, but likely not enough for a company to turn a profit.”

The space station has also enabled commercial collaborations around the world. Bartolomeo, an external platform sponsored by ESA (European Space Agency) and developed by Boeing and Airbus, has 12 active and one passive payload sites with power management, payload commanding, data management and temporary storage, and flight environment determination functions. Potential applications include Earth observation, robotics, materials science, and astrophysics.

ESA’s International Commercial Experiments service, or ICE Cubes, developed in partnership with Space Applications Services and Belgium, offers an affordable, modular platform for experiments. The first investigations the facility hosted included plant biology, microbial bio-mining, and using a person’s heart rate to change a piece of kaleidoscopic artwork.

A Japan Aerospace Exploration Agency (JAXA) experimental facility on the space station — the Japanese Experiment Module (JEM), or Kibo — expands use of the space station for commercial technical demonstrations.

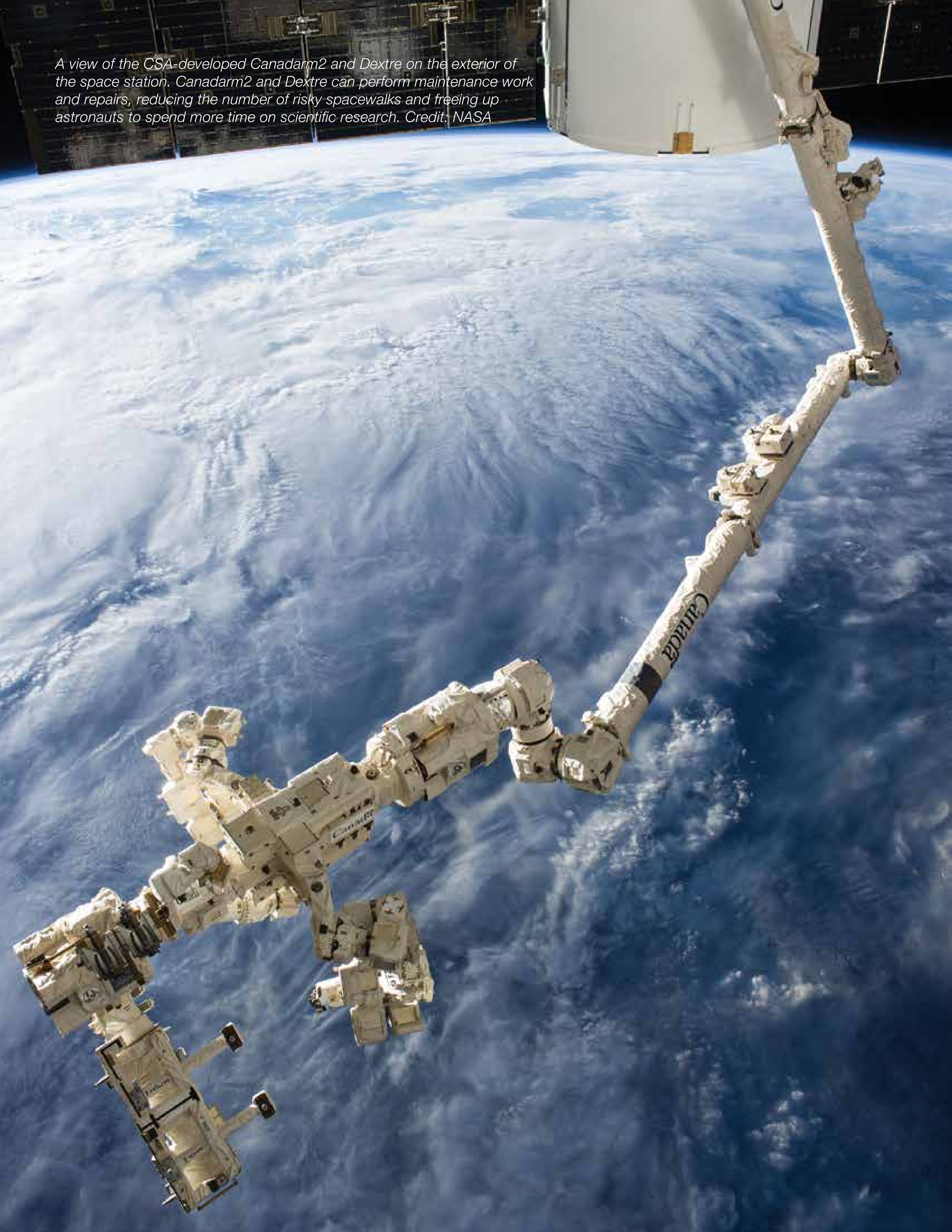
In March 2020, JAXA, along with Japan’s National Institute of Information and Communications Technology (NICT) and Sony Computer Science Laboratories, Inc. (Sony CSL), successfully created a bidirectional laser communication link between an optical communications system on the exterior of Kibo, called SOLISS, and the ground. JAXA and Sony Corporation have worked together since 2016 on research to establish real-time, mass-data communication systems for inter-satellite and satellite-to-ground communications. JAXA, NICT, and Sony CSL continue to conduct detailed analysis and evaluation of the experimental results and anticipate commercialization of the technology in the near future.

Laser communication offers greater ability than radio waves to scale bandwidth, and bidirectional laser communication could greatly increase data transmission speed. Demand continues to grow for faster transmission. This technology soon could help connect more people on Earth, especially those in remote locations.

“These commercial entities are leading the way, working with us, not for us,” said Read. “NASA is in a unique place to enable an economy off the Earth, to create an environment where companies see opportunity. We’ve been fairly successful so far and it is fantastic to be about to take things operational.”

The space station has validated many commercial hardware facilities for researchers to use. In total, there are now more than 30 of these commercial facilities available for space station partners to leverage. The validation of these commercial facilities helps to not only drive research and development on the space station, but also furthers business models in low-Earth orbit and beyond.

“I believe the space station has proven the value of microgravity as a resource,” says Redwire’s Rush. “Its potential to revolutionize fields as diverse as medicine, agriculture, communications, and manufacturing will only drive more commercial interest in the International Space Station and future commercial space stations.”



A view of the CSA-developed Canadarm2 and Dextre on the exterior of the space station. Canadarm2 and Dextre can perform maintenance work and repairs, reducing the number of risky spacewalks and freeing up astronauts to spend more time on scientific research. Credit: NASA

Space Station Spurs Advances in Robotics for Space, Industry

The space station has catalyzed advancements in robotics. Funded by the Canadian Space Agency (CSA), Canadian firm MDA developed Canadarm2 (also known as the Remote Manipulator System) and Dextre, robotic hardware installed on the space station's exterior in 2008. Canadarm2 performs maintenance; moves supplies, equipment, and even astronauts; and catches and berths visiting vehicles. Dextre can install and replace small equipment, such as exterior cameras or batteries, and replace electrical system components. These tools allow astronauts to spend more time doing scientific experiments instead of going on risky spacewalks.

The work to develop Dextre helped advance a technology now in use on Earth, as well. MDA considered giving Dextre a robotic hand with fingers that could grasp, says MDA chief technology officer Cameron Ower. The team found a Canadian robotics professor, Clement Gosselin at Laval University, who had patented such technology but did not yet have a commercial application for it. MDA and the university collaborated on research to adapt the technology to perform operations that could be used on the space station, which evolved into another patented technology, the Self-Adapting Robotic Auxiliary Hand (SARAH). While not ultimately incorporated into Dextre, SARAH's adaptive gripper technology has since become a commonly used component in the burgeoning field of collaborative robotics, helping enable more flexible robotic work cells. In addition, three of Gosselin's graduate students used the technology to start a robotics company, Robotiq.

Swedish company Bioservo Technologies' Ironhand, based on a set of patents from NASA and General Motors' (GM's) Robo-Glove, is the world's first industrial-strength robotic glove for factory workers and others who perform repetitive manual tasks. Credit: Bioservo Technologies/Niklas Lagström

> "Canadarm2 performs maintenance; moves supplies, equipment, and even astronauts; and catches and berths visiting vehicles.

Another space station robot, Robonaut, led to the development of an industrial strength robotic glove. NASA and General Motors (GM) developed a prototype and tested it on the station, where it successfully performed simple tasks alongside astronauts. The team then reconfigured the hand-like part of Robonaut into a wearable device to help both astronauts and auto workers avoid hand fatigue and injury. Initially called Robo-Glove, the device now is commercially available as Ironhand, produced by Bioservo Technologies of Sweden.

"Collaborative robots working alongside a person in an industrial setting made sense, and that spawned more research," Ower says. Assembly line robotics had been around a while when Robotiq was formed in 2008, he added, but collaborative robots and smart systems that can interpret and have a higher level of dexterity were just taking off. "I think this highlights that tackling problems in space and on station drives innovation on Earth. In this case, a non-space idea was pulled into the space world then spun almost immediately back."

Acceptance of robotics in space is spawning additional commercial offerings, he explained.

"At MDA, we are developing a commercial offering for space infrastructure developers and operators, a major investment building on that set of arm technologies and sensing originating from space station robotic technology," Ower said. "In the past five years, about $600 million has been invested in start-up companies focused on in-orbit servicing. It wouldn't have happened without what was shown to be possible on station."

The wide selection of available robotic components includes standardized arms, hands, and cameras, he explained, none of which existed 20 years ago. While MDA has focused on the space applications, activity on the commercial side is increasing.

Miniature Satellites with Massive Benefits

A view taken of CubeSats from Japan, Ghana, Mongolia, Bangladesh, and Nigeria deployed from the Japanese Experiment Module (JEM) Satellite Orbital Deployer 7. Credit: NASA

To witness the space-bound ascension of a satellite assembled by one's own hands is a moment comparable to a parent finally allowing their child to go out and explore the world, according to Izrael Bautista. Not only was it awe-inspiring for the engineering student himself, but also for his country as Bautista watched the second nanosatellite ever sent into orbit by the Philippines launch to the International Space Station.

Bautista made scientific strides for his nation by participating in the BIRDS-4 project, which assists countries in designing, building, testing, launching, deploying from station, and operating their first satellite. This satellite, Maya-2, performed numerous demonstrations, including solar cell and antenna tests.

"It was exciting and scary at the same time because of the uncertainties that could happen during launch and deployment," said Bautista. "Knowing that something with your fingerprints on it is out there in space makes me really proud, and it makes all the time and hard work we put into completing the satellite worth it."

At a standard 10 centimeters (~4 inches) on each side (1 Unit or 1U), these miniature boxes of metal may not seem like they could be of much scientific use within the expanse of space. However, CubeSats have many humanitarian, environmental, and commercial applications. Their modest size and weight of about 1.4 kilograms (3 pounds) drastically reduce launch costs by allowing them to hitch a ride into orbit alongside larger payloads without increasing fuel costs. With over 250 small satellites deployed from the space station, CubeSats are accelerating the growth of the small satellite industry, increasing access to space, and expanding low-Earth orbit research.

Most of these CubeSats have been deployed into low-Earth orbit by the Japan Aerospace Exploration Agency's (JAXA's) Japanese Experiment Module (JEM) Small Satellite Orbital Deployer (J-SSOD) or the Nanoracks CubeSat Deployer (NRCSD). These two systems allow for CubeSats to be prepped inside the station by crew members and passed to the outside of station through the JEM airlock. Thanks to these tools, the permanently crewed orbiting lab has been able to serve as an accessible way for numerous students like Bautista as well as countries and companies to deploy small satellites.

A preflight view of the three BIRDS-4 flight units inside a clean room of Kyushu Institute of Technology. Credit: NASA

U.S.-based company Planet created a collection of CubeSats with the mission to photograph the entire Earth every day and turned to station to test its business model. Aiming to make change visible, accessible, and actionable, Planet has revolutionized the Earth observation industry. Planet's fleet of small satellites provide a bird's-eye view of Earth with small satellites aptly named "Doves."

"Our company goal is to image everywhere very frequently, for everyone," said Planet co-founder Robbie Schingler. "If you image everywhere, then that actually means that you can image anywhere. That's going to be quite transformative for a number of countries, for a number of companies, and so forth."

The first "flock" of Doves was released from station in February 2014. The 28 satellites making up this flock were mounted on the JAXA Multi-Purpose Experiment Platform and placed on the JEM airlock slide table for transfer outside station, making this effort a truly international collaboration. With both its technology and business model maturing, Planet now uses commercial launch providers. However, the Planet story illustrates how the space station can provide early access to space, thereby allowing new business models to prove themselves and attract the investment capital needed to be successful in the marketplace.

Planet has now built and successfully deployed 450 satellites, with over 200 currently in orbit. These daily images do much more than just provide photographs of Earth; they can be used to monitor crop health, track carbon emissions, view urban growth, create current maps, and much more.

Also providing imagery and help to the agricultural community is NASA's CubeSat-compatible Compact Thermal

Imager (CTI), co-winner of NASA's 2021 Invention of the Year Award. This instrument has captured more than 15 million infrared images of Earth with technology that represents the latest advances in infrared detectors. Among the various observations, CTI has helped detect wildfire activity while also monitoring crop health.

"Infrared imaging can play an important role in monitoring crop health and helping members of the agricultural community yield better harvests," said Eric McGill, senior technology manager with the Strategic Partnerships Office at NASA's Goddard Space Flight Center in Greenbelt, Maryland.

The adaptation of small satellite technology has lowered the boundary to entering space, permitting these companies, as well as previously non-space-faring nations, to make strides toward having a presence in low-Earth orbit. CubeSats have become a source of admittance for nations making their first steps beyond planet Earth, and the space station has been key in making that happen.

Since 2015, the Japanese Kyushu Institute of Technology, or Kyutech, has been carrying out the BIRDS program with the goals of capacity building and fostering a long-term

J-SSOD#11 deploys the Joint Global Multi Nation Birds, known as the BIRDS-3 Project. Credit: NASA

and sustainable space organization in participating nations.

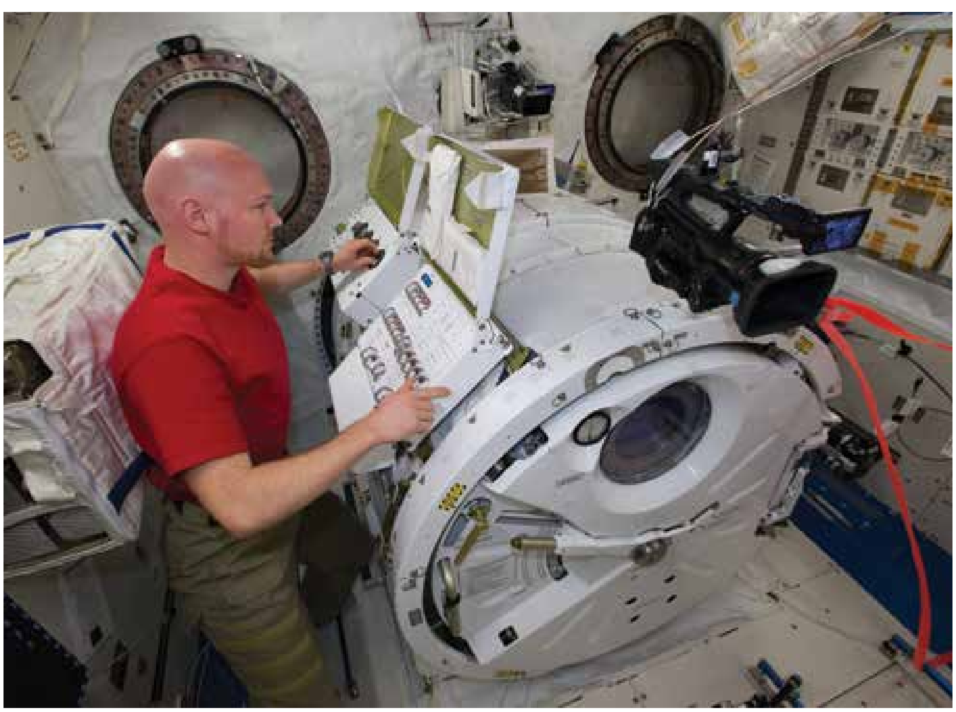
"The project is a bridge to gain space capability for any students who are thinking about getting involved in it. BIRDS creates a rare opportunity, exposure, and abundant network to the space fraternity," said Victor Mukungunugwa, project manager of a BIRDS-5 project for Zimbabwe. As an engineering student representing his country, he says that it has been sensational to work with students from various engineering backgrounds, nationalities, and cultures.

"Two to three students are involved from each country, and BIRDS scientists hope the opportunity has a domino effect as those students go back to their nations," says George Maeda, an assistant professor at Kyutech who works with international students on their BIRDS projects. "For the students, building their nation's first satellite is thrilling beyond words. I see this on a daily basis. It is magic."

The students can teach others what they have learned to continue their involvement in the space community. Bautista exemplifies this objective; his career goals are now focused toward extracting the benefits of space for his country.

"My future is now geared towards developing satellites and their end products," said Bautista. "I will hopefully be able to teach and share what I have learned to the younger generation and be part of our budding Philippine Space Agency."

Another important use for station-deployed CubeSats is testing out new technologies. A student-created project, AzTechSat-1, did just that.



ESA (European Space Agency) astronaut Alexander Gerst depressurizes the Kibo airlock in preparation for a series of Nanoracks CubeSat miniature satellite deployments, including Planet Dove satellites. Credit: NASA

This collaboration between NASA and the Mexican Space Agency demonstrated communications within a satellite network, a capability that could reduce the need for ground stations, lowering costs and increasing data downloads for satellite applications.

AzTechSat team member Rosa Gonzales Cancino was part of a team of students from the Universidad Popular Autónoma del Estado de Puebla (UPAEP).

“The day our CubeSat launched from the space station, it was the longest 40 minutes waiting for a signal. Now it is orbiting the planet, and sometimes that is inconceivable. If I had not held it in my hands, I would think it is a trick or something. I am in space in a way now,” said Gonzales Cancino.

Since she was a child, she has wanted to study the way space affects us all. Now she has seen space work to unify her community.

“On launch day, my whole family got together to watch the launch from my house, and I was moved. I was very excited that despite space not being a topic of their interest, they were all supporting us. That is the same for the entire university. All of the students from all departments were cheering for AzTechSat,” said Gonzales Cancino.

Jose Cortez of NASA’s Ames Research Center in Silicon Valley, California (left), and Joel Contreras of UPAEP (right), conduct final integration of AzTechSat-1 into the Nanoracks CubeSat Deployer (NRCSD) in preparation for launch to the International Space Station. Credit: NASA

The Mexican students behind the AzTechSat-1 CubeSat hold their experiment. Credit: Universidad Popular Autónoma del Estado de Puebla

“I feel that this is also part of the Mexican culture: supporting each other in good times and bad.”

Going forward, new opportunities on station will be opened for students like Gonzales Cancino, and companies like Planet looking to test their technology in space. U.S.-based companies SEOPS and Nanoracks are providing those opportunities by addressing the need for an affordable rideshare for smallsats, and new ways to deploy satellites from station.

With its SlingShot system, SEOPS has created a deployer that hitches a ride on Northrop Grumman’s Cygnus spacecraft and releases smallsats into an Earth orbit above that of the space station. SlingShot offers a flexible, affordable deployment for CubeSats and provides the longer in-orbit time needed to prove technology critical to successful commercialization.

The Nanoracks Bishop Airlock Module serves as another door to space, helping to move larger payloads inside and outside the station. This capability alleviates one bottleneck slowing down the deployment of new small satellites and CubeSats from the space station.

“We’re embarking on more and more public-private partnerships with NASA, building up the ecosystem in low-Earth orbit,” said Nanoracks chief executive officer Jeffrey Manber. “Not only is that important for research opportunities, but it also paves the way for innovations.”

During a What’s On Board Briefing for SpaceX’s 19th Commercial Resupply Services mission to the International Space Station, Rosa Gonzales Cancino, student researcher for AzTechSat-1, discusses her role in the experiment. Credit: NASA

CubeSats Open up Space to More Countries and New Technology Applications

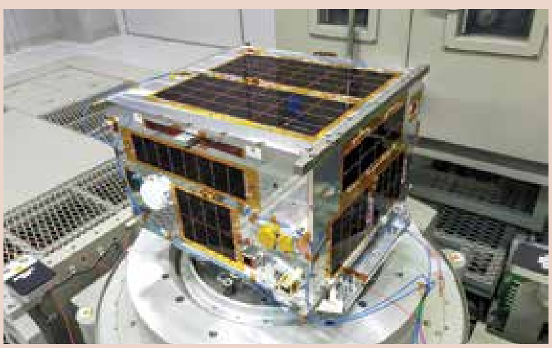
PRCuNaR2

The first satellite deployed by Puerto Rico, known as PRCuNaR2, studied the behavior of collisions among particles in microgravity. Collisions of particles and aggregates of dust play a role in formation of protoplanetary disks – gaseous masses believed to give rise to planets. The investigation could provide insight into this process.

“It has motivated teachers who inspire many students,” said principal investigator Dr. Amilcar Rincón Charris of the Inter American University of Puerto Rico–Bayamon Campus. “I think we are an example to many kids that we, here in Puerto Rico, can do these projects and continue boosting science. The fact that we have a project like this has shown a whole country that the science is worth investing in and that we have talent in the areas of aerospace and the sciences.”

Sponsored by NASA’s CubeSat Launch Initiative, the investigation operated from April to Oct. 2021.

The PRCuNaR2 development team: top (left to right) Hector Gonzalez, Carlos Gibson, Lucas Soto, Amilcar Rincon, Xavier Alvarez, Ian Ortiz, and Jesus Marrer; bottom (left to right) Edwardivan Labarca, Natalie Cruz and Carlos Vergara. Credit: Inter-American University of Puerto Rico



Preflight view of Myanmar’s MMSAT-1 satellite. Credit: Tohoku Hokkaido University.

MMSAT-1

Myanmar’s MMSAT-1, deployed during the JEM Small Satellite Orbital Deployer (J-SSOD) M2 mission, monitors Earth’s surface, including forests, disaster areas, and weather. The satellite uses a high-resolution telescope system, a multi-spectral camera, and a camera with a fish-eye lens. The mission’s goal is to provide information useful for implementing more efficient and systematic agricultural practices and improving the monitoring of natural disasters.

Sponsored by JAXA, MMSAT-1 operated from Oct. 2020 to April 2021.

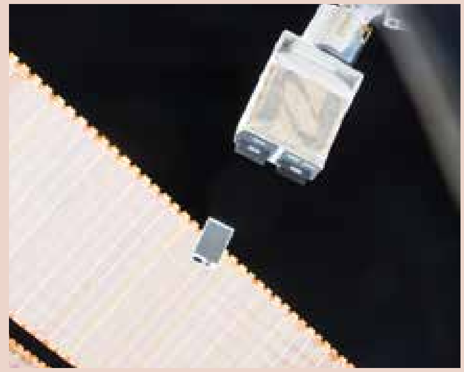
Swiatowid

SatRev was the first Polish company to develop a satellite from electronic components to launch and operate a mission in orbit. Swiatowid, its first project, demonstrated new miniaturization concepts and technologies for the CubeSat market. The project specifically tested whether the 2U CubeSat could provide high-resolution images of Earth using a telescope with an industry-quality camera sensor. Investigators analyzed the images and compared them to images from other sources such as airplanes and other satellites. Use of many small and less-expensive satellites could dramatically reduce the time it takes to obtain Earth images and provide more frequent images of a specific region. This capability has a variety of applications in the burgeoning Earth-imagery marketplace, including research, resource exploration, environmental monitoring, and disaster response.

The ISS National Lab sponsored Poland’s satellite demonstration, which operated from March to Oct. 2019.

The NanoRack CubeSat Deployer (NRCSD)-16 investigation is shown aboard the space station prior to deployment of seven CubeSats that include Swiatowid. Credit: NASA

ASTERIA



This image shows the ASTERIA CubeSat moments after its deployment from the space station's Nanoracks CubeSat Deployer. Credit: NASA

ASTERIA used a 6U CubeSat to test new technologies for astronomical observation, including detection of exoplanets, or planets outside our solar system. Scientists observe the small shadow of a planet as it passes through the light of the star it orbits, which requires repeated observation of stars over a long period of time from a dark environment. ASTERIA used advanced pointing control technology and new thermal stabilization features on the CubeSat platform to perform these complex measurements.

The first CubeSat built by NASA's Jet Propulsion Laboratory (JPL) in Southern California to successfully operate in space, ASTERIA launched in 2017 and continued operating through three mission extensions until the last successful communication on Dec. 5, 2019. During those extensions, ASTERIA tested capabilities for making CubeSats more autonomous and made opportunistic observations of Earth, a comet, Vesta, Uranus, other spacecraft in geo-synchronous orbit, and stars that might host transiting exoplanets.

NASA astronaut Serena Auñón-Chancellor installs the Nanoracks Cubesat Deployer-14 (NRCSD-14), which deployed the RainCube and a variety of other CubeSats. Credits: NASA

RainCube

Climate and weather models depend on measurements from space-borne satellites to complete model validation and improvements. RainCube demonstrated using radar and antenna technology to profile vertically falling precipitation, such as rain and snow, on Earth. RainCube developed a novel, miniaturized radar instrument and demonstrated the feasibility of a radar payload on a CubeSat platform.

The instruments offer reduced size, mass, and power consumption and could provide a low-cost, quick-turnaround platform for future missions. The technology could enable observation of the evolution of weather systems and phenomena on the scale of minutes. Such measurements and observations have the potential to significantly improve climate and weather models and climate science and weather forecasting.

RainCube was developed by JPL and flew in 2018.

Remove Debris

Deployment of the NanoRacks-Remove Debris Satellite. Credit: NASA

Tens of thousands of pieces of debris clutter Earth's orbit. NanoRacks-Remove Debris demonstrates a way to reduce this debris and the risk of satellites and other spacecraft colliding with a piece of it. Investigators and developers from the United Kingdom, Switzerland, France, Germany, and South Africa designed an experiment using two CubeSats, one with a camera to map location and speed of simulated debris and the other with a net or harpoon to capture and deorbit pieces of the debris up to 1 meter (3.3 feet) in size.

Demonstrations successfully produced images and precise locations of intended targets and using a net, captured CubeSats launched to represent debris targets. The captured target was floated away to deorbit and burn up upon atmospheric re-entry in much less time than it would take without intervention. Researchers also analyzed video of the demonstration runs from Earth to learn more about the behavior of debris and how best to remove it.

The project, co-funded by the European Commission and other project partners and led by the Surrey Space Centre in the United Kingdom, flew in 2018.

Canadian Space Agency (CSA) astronaut David Saint-Jacques and NASA astronaut Anne McClain shown installing RRM3 on the space station airlock slide table in preparation for its final home on the outside of the station. Credit: NASA

Catch a Falling Satellite

Space station enables tests of technology to capture, refuel, and repair orbiting satellites

RRM3 hardware shown aboard the space station. This investigation demonstrates the first transfer and long-term storage of liquid methane, a cryogenic fluid, in microgravity. The ability to replenish and store cryogenic fluids, which can function as a fuel or coolant, can help enable long-duration journeys to destinations like the Moon and Mars. Credit: NASA

When satellite fuel tanks hit empty, they can no longer maintain their orbit. If they run out of coolant, some instruments stop functioning correctly. The result can be loss of data and science or disrupted services on Earth. Launching satellites to replace them can be an expensive endeavor but does restore services to Earth. However, the now-defunct satellites may become orbital debris, creating a potential hazard to other spacecraft.

Several investigations have used the International Space Station to test ways to refuel and repair satellites in orbit and avoid these problems.

Beginning in 2011, the Robotic Refueling Mission (RRM) used the space station's two-armed robotic handyman, Dextre, developed by the Canadian Space Agency (CSA), to test NASA-developed tools and procedures needed to refuel and repair satellites that were not originally designed for such servicing. RRM-P2 operated from 2013 to 2016 to refine those tools and procedures, creating the ability for a robot and satellite to work together.

"To refuel a satellite in orbit that was not designed for it requires a series of highly dexterous tasks and special tools to interface between the robot and satellite," said RRM co-investigator Jill McGuire, director of Exploration and In-space Services at NASA's Goddard Space Flight Center in Greenbelt, Maryland. "So, we built innovative tools to bridge the gap between the robot and the payload."

That paved the way for RRM3, which launched in 2017 and already has successfully demonstrated the first in-space transfer of cryogenic fluid, which can function as a fuel or coolant. The Zero Boil-Off Tank (ZBOT) study worked with a different aspect of cryogenic fluid, using an experimental fluid to test an alternative means for controlling tank pressure for storing coolant. This is the first in a series of experiments to advance our knowledge in the development of lightweight, efficient, and long-duration cryogenic propellant storage tanks in space.

In addition to extending the life of existing satellites, these investigations provide guidance for designing future satellites that can be more easily serviced – and, therefore, keep providing important services to people on Earth.

NASA astronaut Christina Koch handles media bags that enable the manufacturing of organ-like tissues using the BioFabrication Facility (BFF), a 3D biological printer. The BFF could become part of a larger system capable of manufacturing whole, fully functioning human organs from existing patient cells in microgravity. Credit: NASA

Building a Better Future in Orbit

How in-space manufacturing is bringing change to life on Earth

An average of 22 people die each day in the United States waiting for a donated organ. Upwards of 30 million people worldwide suffer from degenerative retinal diseases. New manufacturing processes are being developed aboard the International Space Station that could help address both issues.

Microgravity provides a unique opportunity for companies, creating everything from bioprinted organs to a high quality of materials not achievable on Earth. In making the business case, high-demand products that address significant unmet needs or that have a high return on investment are at the top of the list for creation in orbit and return to our planet. It turns out that research at the intersection between biotechnology and medicine, something that seems straight out of science fiction, may fit that bill.

A microscopic image of a section of ZBLAN optical fiber produced by the second iteration of Fiber Optic Production aboard the International Space Station. Credit: Mercury Systems

U.S.-based biotechnology company LambdaVision is designing and developing a protein-based artificial retina, using a light-activated protein, that could replace the function of damaged photoreceptors in the eye. The aim is to restore functional sight in those with blindness caused by retinal degenerative diseases, which include age-related macular degeneration and retinitis pigmentosa. Currently, no cure is available for either of these diseases, thus there is a significant unmet need to develop a technology to restore meaningful vision to these patients and improve their quality of life.

The ISS National Lab-sponsored Protein-Based Artificial Retina Manufacturing investigation evaluates the use of the protein bacteriorhodopsin in a layer-by-layer deposition process to create thin films that can be inserted into the subretinal space. Those created on station are expected to have better quality and stability than those manufactured on Earth.

"In a microgravity environment, we expect more homogeneous and consistent layering," said principal investigator Nicole Wagner, president and chief executive officer of LambdaVision. "On Earth, we construct the artificial retina using a layer-by-layer process that is very much subject to the effects of gravity. Manufacturing in microgravity allows us to avoid sedimentation of solutions and aggregation, which can produce thin films with fewer defects, higher homogeneity, and enhanced optical clarity."

LambdaVision researchers and their implementation partner Space Tango were able to manufacture a 200-layer film in microgravity for the first time — an important step in their studies.

Many commercial manufacturing operations are taking advantage of microgravity's reduction in errors caused by gravity on Earth. Made in Space Fiber Optics examines fiber optic filament manufacturing in microgravity using a material called ZBLAN, a blend of zirconium, barium, lanthanum, sodium, and aluminum. This optical fiber glass can perform 100 times more efficiently than traditional silica-based fibers, according to the ISS National Lab.

Researchers believe that these optical fibers, used for ultra-high-speed broadband communications and remote sensing, could exhibit far superior qualities when produced in microgravity. Several studies are putting this theory to the test, seeing whether low-Earth orbit can house commercial manufacturing of these fibers for use on the ground.

ISS National Lab sponsored Fiber Optic Production-2 (FOP-2) expands upon earlier work, helping construct a process to aid future manufacturing of high-quality optical fiber of the highest value for commercial businesses.

Also returning to Earth from orbit could be actual 3D-printed human cells. Several companies are working toward the creation of human organs using microgravity as a tool. Bioprinting, a subcategory of 3D printing, uses viable cells and biological molecules to print tissue structures. A first-of-its-kind bioprinter launched by Russian state space agency ROSCOSMOS (ROSCOSMOS) in 2018 helped pave the path for research on artificial organ creation. Specialists from Russian company 3D Bioprinting Solutions developed special scientific equipment called 3D MBP, which consists of a magnetic bioprinter, Organ.Aut, and a set of multifunctional transparent cuvettes. Organ.Aut's capabilities include culturing cartilage cells in space through the use of magnetic fields.

Japan Aerospace Exploration Agency (JAXA) astronaut Norishige Kanai poses for a photo with the installed Made in Space Fiber Optics Locker and the re-installed Additive Manufacturing Facility (AMF) manufacturing device. The Made In Space Fiber Optics investigation demonstrates the merits of manufacturing fiber optic filaments in microgravity. Credit: NASA

A series of experiments performed on station from 2018-2020 proved the scientific importance of this approach for the creation of tissue constructs (platforms for research), obtaining stable biofilms of bacteria and studying the processes for synthesizing mineral components of bones and crystallizing organic molecules. These results pave the way for the development of innovative treatments that include tissue engineering products and next-generation medicines.

Astronauts currently use the BioFabrication Facility (BFF) to test the creation of biofabricated tissues in microgravity. Techshot, a Redwire company that built and runs the facility, is looking to capitalize on the increased opportunities for commercial businesses in space. Techshot launched BFF in 2019 and since then has been working toward the goal of developing the capability to solve the problem of organ shortage.

Nicole Wagner, President and CEO for LambdaVision Inc., speaks to members of the media in the Kennedy Space Center's Press Site auditorium. Credits: NASA/Kim Shiflett

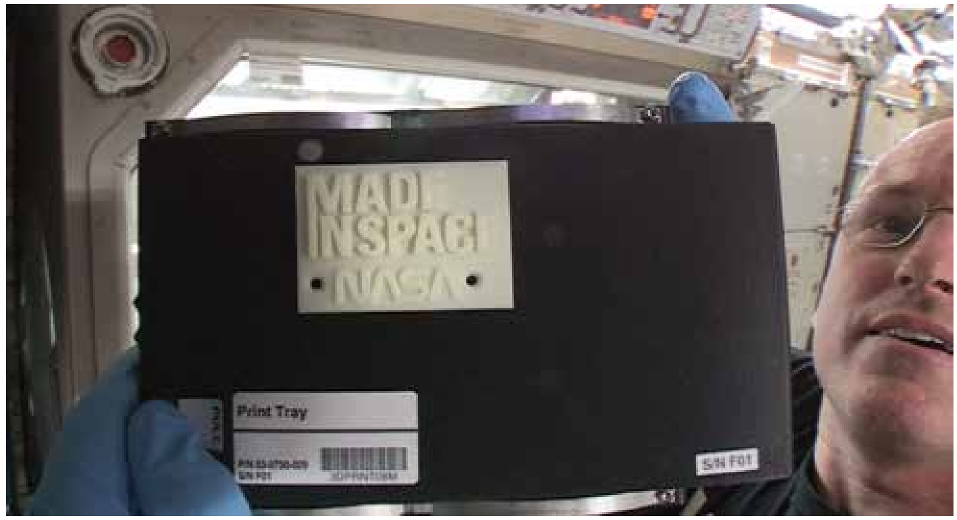
"There will never be a solution available if we don't take the first step," says Richard Boling, vice president at Techshot. BFF already has printed multilayer cardiac constructs as well as preliminary test prints of components of a human meniscus.

On Earth, bioprinted constructs either collapse or require chemical thickening treatments, both of which render the cells incapable of replicating human organ tissue. Microgravity makes it possible to print complex multilayer constructs and compile them into tissue with a two-pronged process. First, cells are printed in repetitious layers using the BFF. A second piece of Techshot hardware, the ADvanced Space Experiment Processor (ADSEP), conditions these cells into tissues.

While the focus of this project is better health for those on Earth, these two hardware systems also may play a role in production of food or medicine during deep space exploration.

"We provide the picks and shovels researchers use to make new discoveries and improve life on Earth,"

ESA (European Space Agency) astronaut Matthias Maurer is shown during preflight training for the BioPrint First Aid investigation, which tested a bioprinted tissue patch for enhanced wound healing. Credit: ESA



Commander Barry "Butch" Wilmore holds up the first object made in space with additive manufacturing or 3D printing. Credits: Made in Space/Redwire Space

says Boling. "Feed people and heal them, what more would you want to do to benefit humanity? To me, the space industry is less about the rings of Saturn and more about humanity, whether making life better on Earth, or extending life to Mars."

Bioprint FirstAid, a study from the German Space Agency (DLR), focuses on bioprinting for exploration. It demonstrates a portable, handheld bioprinter that uses a patient's own skin cells to create a tissue-forming patch to cover a wound and accelerate the healing process.

On future missions to the Moon and Mars, bioprinting such customized patches could help address changes in wound healing that can occur in space, which complicates treatment. Extracting an individual's cells before a mission would enable more immediate response to injury. Similar 3D printing technology could help address another issue with long-duration spaceflight: limits on the ability to predict every tool or object needed for missions beyond the lunar surface. One way to avoid "over packing" is to bring technology to create any fixture the crew may need during the spaceflight.

The first 3D printer in microgravity, a plastic-based machine, arrived on station in 2014. Developed by Redwire Space (formerly Made in Space), the machine combined heat with the plastic in a singular-layering process to manufacture objects on demand.

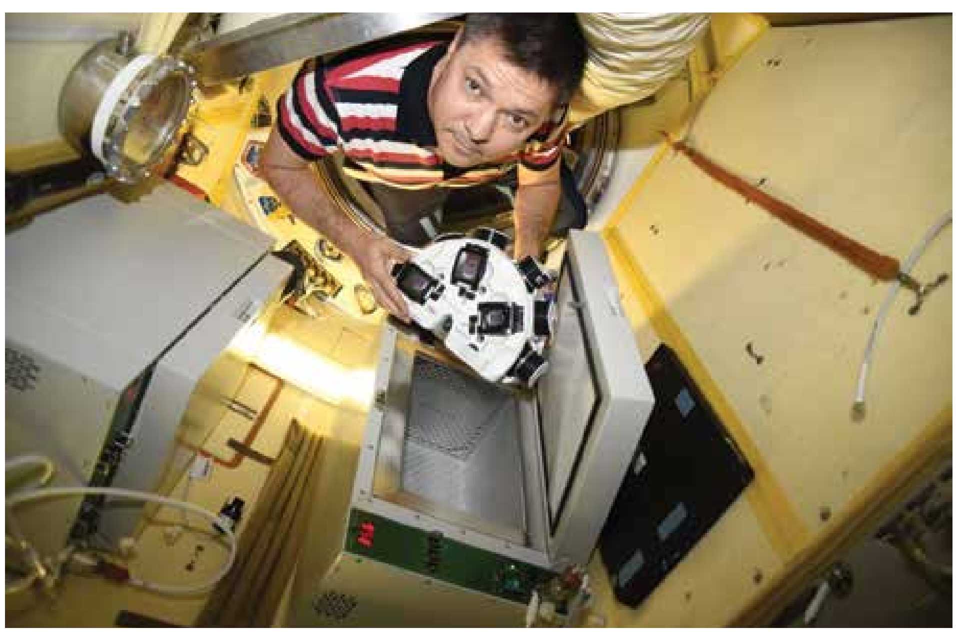
The 3D Printing In Zero-G experiment opened the door to this possibility by demonstrating that a 3D printer works normally in space. The Italian Space Agency (ASI) and NASA also collaborated on the Portable On Board Printer 3D experiment, which further paved the way for printing on station. Now hundreds of samples have been created using multiple printing facilities.

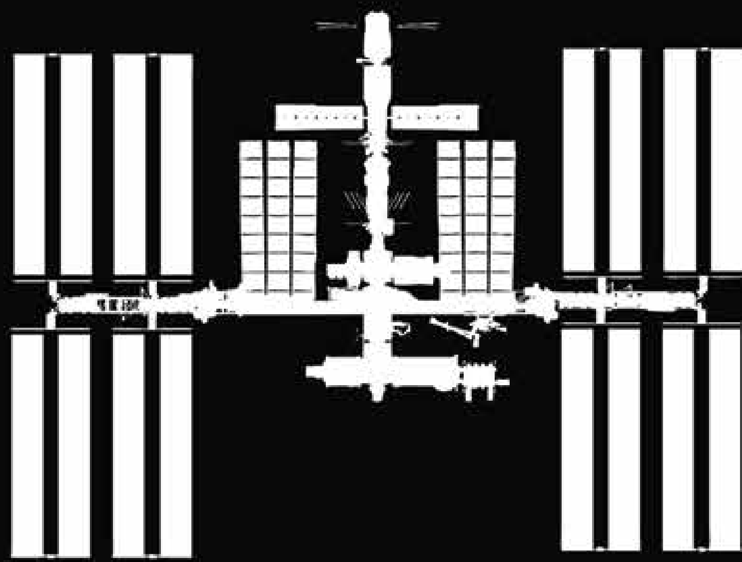
In general, these printers extrude streams of heated plastic, metal, or other material, building layer on top of layer to create three-dimensional objects. Testing this process using relatively low-temperature plastic feedstock on the space station was an important first step toward establishing an on-demand fabrication capability for deep-space crewed missions and in-space manufacturing.

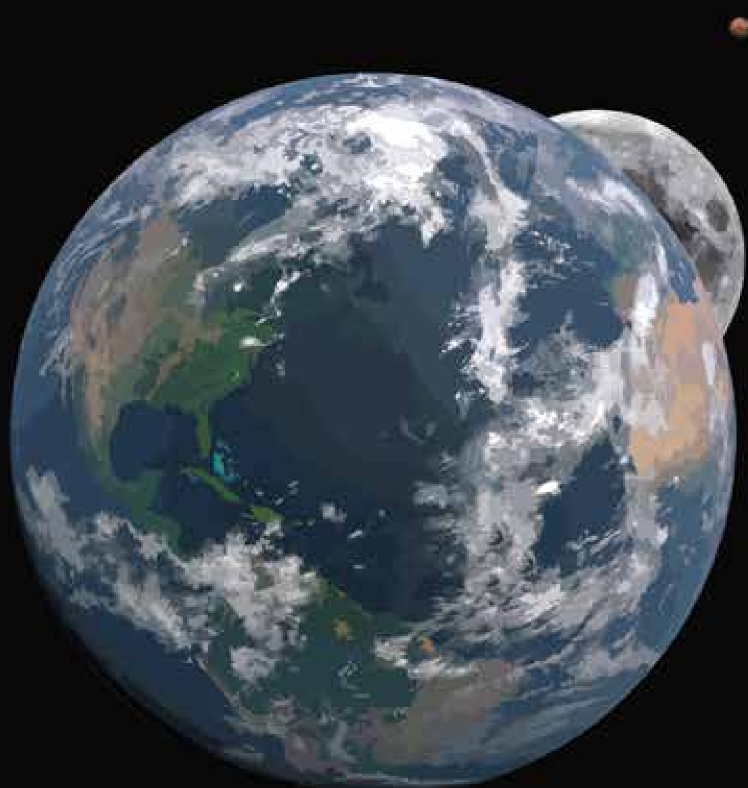
Minimizing waste is of the utmost importance aboard the space station and will be crucial on long-duration missions. NASA's Refabricator, the first 3D Printer integrated with a recycler aboard station, recycles plastic waste into high-quality 3D printer filament. Successfully demonstrating sustainable manufacturing, repairing, and recycling is a key initiative for NASA.

The Redwire Regolith Print (RRP) demonstration took this concept to the next level by examining an entirely different kind of feedstock for 3D manufacturing on the orbiting laboratory: regolith. This dust, present on the surface of the Moon and other planetary bodies, could provide raw materials for construction of habitats and other structures. Using regolith would reduce how much material must be launched on future missions.

Exploring the next frontier of manufacturing off the Earth gives commercial partners the opportunity to explore the capabilities of production in microgravity for use on Earth and on long-duration space missions. As with many advanced scientific concepts relating to space, the space station seemed like a fictional concept in the mid-20th century. Now it is bringing to reality futuristic ideas for manufacturing.


Russian cosmonaut Oleg Kononenko floats aboard the International Space Station with the 3D MBP. Credit: ROSCOSMOS





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