INTERNATIONAL SPACE STATION

BENEFITS FOR HUMANITY

3RD EDITION

International Space Station Benefits for Humanity

3RD Edition

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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Executive Summary

The third edition of the International Space Station Benefits for Humanity is a compilation of benefits being realized from International Space Station (ISS) activities in the areas of human health, Earth observations and disaster response, innovative technology, global education, and economic development of space. This revision also includes **new assessments of economic value and scientific value** in more detail than the second edition. The third edition contains updated statistics on the impacts of the benefits as well as new benefits that have developed since the previous publication. International Space Station Benefits for Humanity is a product of the ISS Program Science Forum (PSF), which consists of senior science representatives across the ISS international partnership.

With respect to **economic valuation (EV)**, the journey from fundamental research and development to full commercialization can be long, often taking decades for a useful product or application of new knowledge to evolve and positively influence society. As this process unfolds, some products and services derived from space station activities are already entering the marketplace and benefiting lives on Earth. Using research conducted by Navigant Consulting, Inc., the EV section examines some of the early economic returns on the research accomplishments enabled by the orbiting laboratory. It also touches upon the role the space station has played in nurturing the growing space economy and the increasing interest in space by the private sector.

With respect to **scientific valuation (SV)**, the unique microgravity environment and the international and multidisciplinary nature of the research on the ISS offers a significant challenge when analyzing the scientific value of the orbiting laboratory. The ISS Program Science Office has used many different methods over the years to describe the knowledge impacts of ISS research activities. Results publications are continuously updated and posted at http://www.nasa.gov/stationresults. As of May 2018, the ISS Program identified more than 2,100 publications since 1998, with sources in journals, conferences, and gray literature. After years of evaluating ISS scientific results in many different ways to determine its impact on the world, one pattern remains clear: space station research has a large global and interdisciplinary impact on scientific advancement. This edition's SV section illustrates that impact.

Finally, this book summarizes the accomplishments of research on the space station that have had and will continue to have a positive effect on the quality of life on Earth. Through advancing the state of scientific knowledge of our planet, improving our health, developing advanced technologies, and providing a space platform that inspires and educates the science and technology leaders of tomorrow, these benefits represent the legacy of the ISS as its research strengthens economies and enhances the quality of life here on Earth for all people.

Introduction

Welcome as we share the successes of the International Space Station (ISS) in this third edition of the International Space Station Benefits for Humanity. The ISS is a unique scientific platform that has enabled more than 3,600 researchers in 106 countries and areas to conduct more than 2,500 experiments in microgravity through February 2018—and the research continues.

Since November 2, 2000, the ISS has maintained a continuous human presence in space. Research began on the orbiting laboratory even before it was occupied. In 2011, when ISS assembly was complete, the focus shifted to fully utilizing the lab to promote scientific research, technology development, space exploration, commerce, and education.

The ISS began as an **engineering achievement** that evolved over a decade. Its components were built in various countries around the world. The coordination required to accomplish this without testing the fully assembled structure on Earth allowed us to learn a vast amount about the construction of large, complex technical systems. This **international achievement** illustrates the cooperative teamwork required to create an international partnership that has continued to flourish and serve as a model for international cooperation. Although each ISS partner has distinct research goals, the unified goal is to extend the knowledge gleaned to benefit all humankind. The **research achievement** of the space station has been demonstrated through the application of its technical capabilities (similar to those in ground-based laboratories) to the unique conditions of the low-Earth orbit environment, which has consistently achieved meaningful scientific results. Subsequently, the **economic achievement** of the space station has been realized through use of its technical capabilities as well as changes to contracting mechanisms, which have given rise to new companies, patents, and products.

Value of the Platform

The Engineering Achievement

The International Achievement

The Research Achievement

The Economic Achievement

In the first edition of this book, released in 2012, the scientific, technological, and educational accomplishments of ISS research that impact life on Earth were summarized through a compilation of stories. The many benefits being realized were primarily in the areas of human health, Earth observations and disaster response, and global education.

The second edition, released in 2015, included updates on the first edition benefit areas (including new stories in those areas), plus the addition of two new benefit areas: economic development of space and innovative technology.

This third edition includes updates to the second edition's five benefit areas (including new stories in those areas), plus two new sections on the economic valuation and scientific valuation of space station research.

Benefits of Research and Technology

Space exploration requires innovation, which results in discovery and benefits for humanity. Innovation creates new technology and discovery results in new knowledge—and both of these create economic opportunity, which provides the infrastructure to enable further exploration.

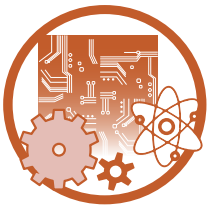
Benefits for Humanity Themes

Scientific Valuation

Economic Valuation

Human Health

Earth Observation and Disaster Response



Innovative Technology

Global Education

Economic Development of Space

View of solar array and radiator panels over Earth limb taken during Russian EVA 43 by Expedition 52 crew.

Image credit: NASA

Economic Valuation of the International Space Station

Maturing theories, potential applications and valuable products all rise from the new knowledge and capabilities generated through International Space Station research activities. Those that meet the challenges of corroborative testing, or find a sustainable market niche, generate commercial activity and social benefits. As this process unfolds, some products and services derived from the space station activities are already entering the marketplace and benefiting lives on Earth. Supported by research performed by Navigant Consulting, Inc., a global professional services firm with decades of experience in the evaluation of research and development programs, this section will examine some of the early economic returns on the research accomplishments enabled by the orbiting laboratory. It will also touch upon the role the space station has played in nurturing the growing space economy and increasing private-sector interest in space.

International Space Station Economic Value

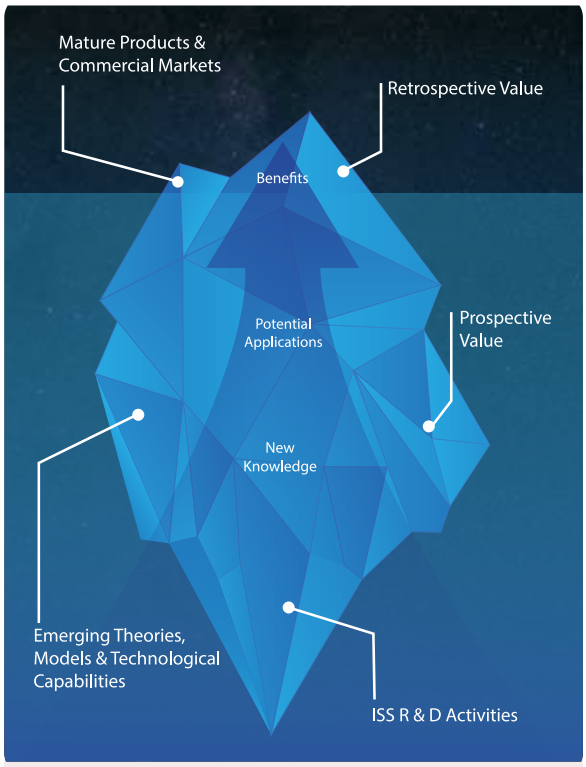
In the 20 years since the first International Space Station (ISS) module was launched, access to the environment of low-Earth orbit (LEO) for researchers around the globe has made gravity another variable for their experiments. Since 1998, the ISS has enabled more than 2,500 research and technology development (R&D) investigations, generating more than 2,100 scientific publications across a diverse spectrum of fields. The Scientific Value section provides many examples of new knowledge and data sets generated or refined through ISS activities. As this new knowledge begins to shape the thinking of researchers and technological innovators back on Earth, new commercial products and ventures are beginning to emerge and new lines of research are being explored—all demonstrating how space exploration and the unique features of microgravity and space-based research can improve our lives here at home.

The process of generating concrete economic value from space-based ventures often resembles the proverbial long-and-winding road. Likewise, the many milestones and activities on the road to a mature product can make it difficult to trace benefits back to ISS beginnings. With these caveats in mind, this subsection aims to illustrate the benefits of the ISS by providing representative examples of ISS R&D activities and ISS-derived technologies, and tracing their forward influence on emerging companies and products, lines of research and the growing commercial marketplace in LEO.

From Research and Development to Tangible Benefits

The journey from fundamental research, or technology development, to full commercialization can be long. In fact, it can take many decades to go from initial conception, or discovery, to a useful product or application of knowledge. In many ways, it can be instructive to think of this in terms of an iceberg. Innovative scientific research and technological development can be thought of as a source of possibilities and potential uses. From this base of **new knowledge** and capabilities, emerges a finite set of promising theories and **potential applications**. These emerging, or prospective, benefits must stand up to rigorous corroborative testing in the case of new theories, or find a sustainable market niche in the case of new products. In our iceberg analogy, the subset of maturing technological products and scientific theories

…mWater was able to work with competitors to improve lives around the world through the use of its mobile application.



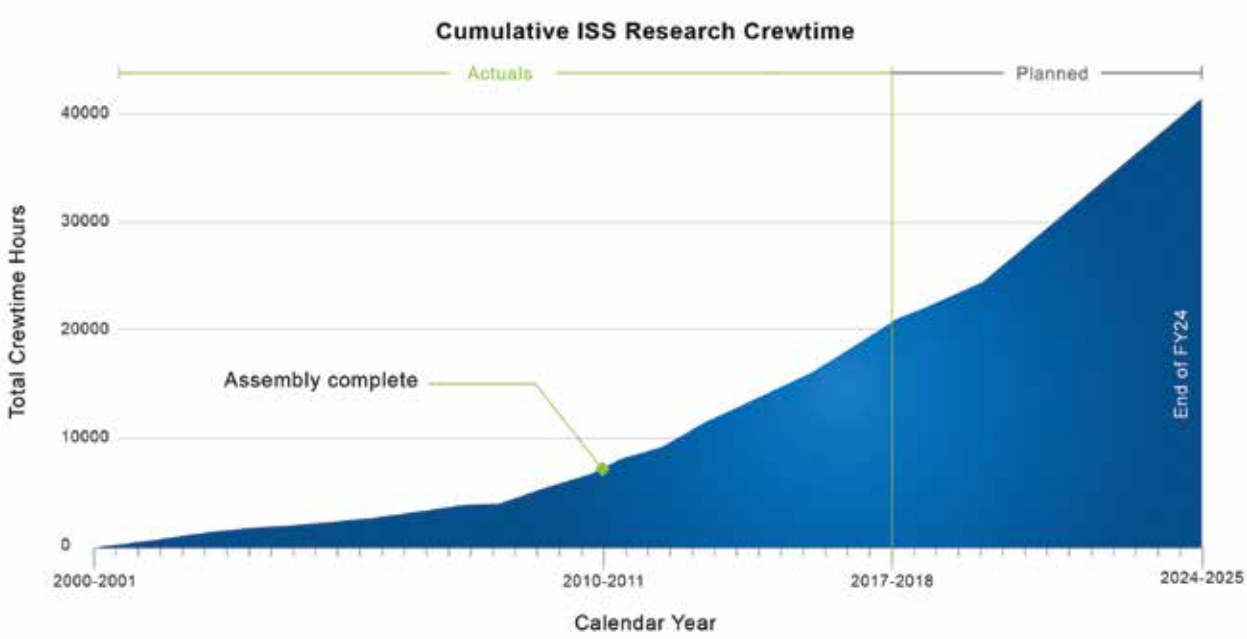
Generating value from research endeavors.

Image credit: MAPI/NASA

that meet these challenges rise above the surface of the water, generating increased commercial activity and adding to quality of life. These are the concrete, or retrospective, benefits derived from ISS activities.

Applying this analogy illuminates a couple of pitfalls to avoid when evaluating the economic value of ISS research endeavors. For one, focusing exclusively on the concrete benefits already above the surface, derived in the relatively short period of time the space station has been in orbit, one can easily overlook the significant amount of new knowledge and innovative technical development being generated below. In addition, although initial research efforts began shortly after the first module was orbited in 1998, assembly of the space station was the top priority through the next decade. As illustrated by the accumulation of crew hours devoted to investigations aboard the ISS, research has taken priority in only the last 6 to 8 years. At the same time, new research facilities have steadily been added since 2011, with capabilities to control and monitor experiments from the ground, thereby substantially expanding the numbers of investigations that can take place simultaneously. As a result, 166 research investigations were conducted during the first six crew rotations on space station, while 416 investigations were conducted during the last six crew rotations. Since both the crew hours devoted to research and the capabilities to conduct multiple experiments simultaneously have increased significantly in the past 6 to 8 years, much of the research results generated on the space station are still in early stages of evaluation by the primary investigators. The dissemination of the new knowledge to the greater scientific community is also in its early stages.

The data collected by the Alpha Magnetic Spectrometer (AMS-02) investigation exemplify this time lag. The AMS-02 is a particle physics detector intended to help answer fundamental physics questions, such as “What makes up the universe’s invisible mass?” or “What happened to the primordial antimatter?” The AMS-02 was installed on the ISS in May, 2011 and had collected data on more than 90 billion cosmic ray impacts by 2016 when initial results were published (http://www.ams02.org). Although the data have provided support for some theories of dark matter and spurred debate about the existence of new astrophysical phenomena, more time is needed for the physics community to fully digest the data, and for new or modified theories to be tested.



Cumulative crew time allotted to research.

Image credit: NASA

The AMS-02 investigation is a good example of what can be missed if one focuses purely on concrete economic benefits, to date. While a better understanding of the universe is intrinsically valuable, the sum total "payoff" of that knowledge is impossible to predict and likely to take a long time to reveal itself.

Conversely, focusing on the many promising lines of application that fizzle out before they rise above the surface and make a lasting impact can also distract from the steadily growing stream of benefits that history indicates will come over time. For example, one of the narrative stories in previous editions of this publication focused on an innovative company, mWater, which used knowledge derived from ISS systems to develop and market a $10 water testing kit. Although the product is sound, it has not gained significant market share over larger competitors. However, the accompanying mobile application—mWater Surveyor, which records water testing results and aggregates that data worldwide—has become the largest such database in the world, kept up to date with as many as 70,000 survey submissions per month from 150 countries. According to the mWater website, with partners including USAID, UNICEF, WHO, and the World Bank Innovation Fund, more than 25,000 NGOs, governments, and researchers are using the mapping and monitoring data around the world.

The mWater story illustrates how positive benefits can be found, even when a particular product does not succeed in the marketplace. As a nonprofit, mWater was able to work with competitors to improve lives around the world through the use of its mobile application, while continuing to maintain intellectual property in water filtration and test-kit products, and pursue a sustainable market niche.

Having defined and illustrated the challenges of conducting economic valuation of research and development activities, the economic valuation conducted on ISS R&D activities will be described next. The results obtained will follow that description with several illustrative examples discussed in some detail.

Description of Valuation Process

To characterize the impact of the ISS to date, Navigant Consulting, Inc., was tasked with applying a value impact methodology customized for space research based on best practices across federal laboratories, commercial companies and leading nonprofit research organizations. Navigant is global professional services firm with decades of experience in the evaluation of R&D programs ranging from supporting the decision-making of organizations with R&D portfolios valued in the hundreds of millions to billions of dollars as well as the research selection process of the ISS U.S. National Laboratory.

Navigant conducted rigorous, independent due diligence similar to the work the firm executes in support of technology/IP valuations, private equity and financial transactions, utilizing its in-house and extended network of engineering, science and technology expertise. Navigant's approach was to place each activity in a market context and explore issues such as market dynamics, technology readiness, competitive forces, and management depth to assess and consider potential outcomes.

Selection of activities for economic evaluation is complex. Most early ISS research and development activities were chosen based on scientific merit rather than economic value. However, a number of these have economically relevant outcomes as case studies. Conversely, R&D activities selected for the U.S. National Laboratory on the basis of economic value are more recently flown; therefore, the time for development of economically relevant applications post-flight has not been sufficient for measurement. Only a small selection (40) of the ISS R&D activities could be evaluated due to the effort involved in evaluating the development of economic value after the flight activity is complete. Recognizing that less than 2% of all investigations could be evaluated, all international partners were engaged in determining which were selected for review. Navigant evaluated the 40 ISS activities on three dimensions of value: innovative, humankind/social and economic.

Assessment of *innovative value* was derived by an evaluation of possible impacts research leadership may have in a specific area. This evaluation includes considerations on how the research may generate new or improved products, services, processes, or knowledge as compared to traditional approaches. Key questions used to drive this dimension of the analysis are "Does the research provide a leadership position?" and "Does the research provide a critical

Navigant evaluated the 40 ISS activities on three dimensions of value: innovative, humankind/social and economic.

solution in an area where there is little incentive for other government, commercial, and/or academic investment?"

Assessment of *humankind/social value* was developed by analyzing factors including, but not limited to, quality of life improvements, health benefits, environmental benefits, cultural and community cohesion, inspiration, and the effects the submitted case may potentially have upon current and future generations. The impact that the case may potentially have upon society as well as personal and property rights were also considered key elements in the evaluation of humankind benefits.

Assessment of *economic value* was based on the analysis of publicly available information related to the submitted cases, including but not limited to domestic and internationally sourced economic evaluations, academic sources and industrial sources related to the submitted cases. Economic indicators such as market penetration, revenue generation, cost-benefit analysis, future industry outlook and limitations on accessibility were all potential factors considered in the economic valuation. The assessment included both retrospective and prospective economic benefits related to each case.

These three dimensions of value can be tied back to the iceberg illustration. Innovative value is a measure of the potential impact of the new knowledge and technical "know-how" being generated through ISS research and development efforts. Prospective economic and social value are measures of the emerging scientific theories, computer models and technological breakthroughs rising out of that potentiality toward concrete application. Finally, retrospective economic and social benefits rising above the water line, such as companies formed, products brought to market, and lives impacted, indicate the "early returns" of our ISS investment—benefits already demonstrating value at this time.

Valuation Results

Findings of the Navigant valuation review can be found throughout this publication in sidebars located next to the relevant stories. In all, Navigant identified concrete or emerging economic value indicators for 25 of the 40 activities submitted for review. The remaining 15 showed innovative value and potential applications. In these cases either the research was too recent to have generated more than broad possibilities, or detailed information was not publicly available.

The Summaries of Valuation Findings table found at the end of this section lists key findings as grouped by primarily innovative, prospective (potential), or retrospective (concrete) findings. Taken as a whole, these findings exemplify the diverse benefits generated to date, as well as some of the potential benefits yet to come. Some of these benefit examples are discussed in greater detail below and serve to illustrate common characteristics of the paths taken as new knowledge bubbles up toward concrete benefits.

From New Knowledge to Potential Application: Generating Prospective Benefits on the International Space Station

As discussed above, fundamental research and development efforts on the International Space Station (ISS) are many and varied in their scope. These efforts have generated new knowledge and technological capabilities from which potential benefits emerge in the form of new theories, data sets and conceptual applications. A series of investigations known as Flame Extinguishment (FLEX) provide one such example of new knowledge being generated. Protein crystal growth and nanofluidics are areas of research for which the potential applications hold the promise of emerging benefits in the near future.

Combustion Studies

FLEX was conducted to research the properties of fire suppressants in space, and to better understand combustion and soot production in microgravity. These investigations uncovered a new form of combustion occurring at a lower temperature than previously observed (370°C [700°F] vs 760°C [1,400°F]). In 2017, follow-on FLEX investigations uncovered a second "cool flame" phenomena with temperatures even lower—roughly 200°C (400°F).

> These investigations uncovered a new form of combustion occurring at a lower temperature than previously observed…

The FLEX investigations are a good example of new knowledge that has innovative value. As researchers unravel the mechanisms of cool flames, this new knowledge has the potential to lead to more-efficient, lower-emission liquid combustion engines. Transportation-related emissions account for nearly 23% of energy-related carbon dioxide emissions worldwide. In the United States transportation sector, engines account for nearly 50% of all nitrogen oxide emissions and over 66% of particulate matter (soot) emissions. Thus, this new knowledge could lead to significant humankind benefits and economic value. However, as with all emerging new knowledge, concrete benefits are far from assured. Additional research is necessary and many practical challenges must be overcome before one or more concrete applications of this new knowledge emerge years, or even decades, from now.

Protein Crystal Growth

Another area of research benefiting from the ISS is protein crystal growth (PCG). The unique microgravity environment of the ISS allows for the growth of larger, higher quality protein crystals than those that can be grown on the ground. When returned to Earth, these crystals are imaged to reveal previously unknown structural details. Even though the conditions often need to be optimized across multiple flights to achieve larger, higher quality crystals, PCG on the space station holds the promise of reducing overall research costs for pharmaceutical companies, thereby allowing them to more accurately predict how candidate drugs

will perform and more precisely model the structure of key proteins involved in disease.

As mentioned in their partner perspective below, commercial experiments in support of pharmaceutical research are a major focus of the Japan Aerospace Exploration Agency (JAXA) ISS activities. The ISS U.S. National Laboratory also hosts a significant number of PCG experiments. Many pharmaceutical companies, including Eli Lilly, Merck, Taiho Pharmaceutical, and PeptiDream, have conducted PCG investigations on the space station. These activities provide many examples of potential humankind benefits, which would have high economic value as well.

One such investigation, JAXA PCG, crystallized a protein of interest to researchers focused on Duchenne's muscular dystrophy (DMD). DMD is a severe condition that causes progressive muscular degeneration, often leaving the affected patients unable to walk by early adolescence. In 2002, a research investigation revealed a specific protein (H-PGDS) that was expressed in necrotic muscle fibers in DMD patients. This discovery fueled the development of specific inhibitors of H-PGDS as potential therapeutic agents, and motivated researchers to grow macroscopic protein-inhibitor complexes to map the structures at the highest resolutions. The analysis of the structure of H-PGDS and inhibitor complex grown as part of the JAXA PCG investigation on the ISS led to an improved complex structure (TAS-205), which is considerably more effective inhibitor than those under investigation at that time. Subsequent tests showed that TAS-205 did reduce or slow the expansion of muscle necrosis in mice and dogs. In 2015, the multinational Taiho Pharmaceutical Corporation verified that the TAS-205 inhibitor is safe for use in humans.

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In 2017, TAS-205 completed a 24-week Phase II trial with 33 human DMD patients.

Merck Research Laboratories is conducting PCG research onboard the ISS to develop a subcutaneous (SC) formulation of the immunotherapy drug, Keytruda, which is currently administered via an intravenous (IV) injection. SC reformulations of similar drugs, such as Herceptin, provided a 44% savings in time and a 77% savings in medical staff effort over IV delivery. In addition, over 90% of patients preferred the SC formulation due to reduced pain, discomfort and side effects. Also, if the SC reformulation is more stable at room temperature, it will reduce costs associated with storage and transportation.

Forbes analysts state that Merck's first quarter growth in 2018 can be attributed primarily to growth in the oncology segment, notably through Keytruda's year-over-year growth to $1.46 billion. Through advances in delivery mechanisms such as SC reformulations, Merck may be able to further capitalize on Keytruda's potential sales.

The PCG line of research with its potential new therapeutic drugs, as well as the nanochannel-based delivery mechanisms that can reduce or eliminate visits to the doctor's office and increase the percentage of patients who take the proper dosage on time, illustrates how investigations aboard the ISS can lead, over time, to emerging applications on Earth with significant potential humankind benefits and economic value.

However, rapid and repeat access to test multiple crystallization conditions is an important factor that underlies the success or failure of specific efforts on specific proteins. Not all PCG efforts will result in improved crystals or structures in spaceflight. However, each protein that is successful, as will be illustrated in the next section on maturing and concrete benefits, has the potential for significant economic impact if it can be developed into a new approach for treating disease.

Earth Observation Data

Data sets generated by the many Earth observing instruments hosted on ISS external platforms are another source of new data being exploited for economic benefit. For example, using ISS-generated Earth observation data, Dr. Ruhul Amin of the U.S. Naval Research Laboratory refined remote detection algorithms to identify harmful algal blooms. A spin-off company, BioOptoSense LLC, has been formed to market this detection capability. The University of Mississippi, City College of New York, and the Naval

Research Laboratory have already used the BioOptoSense algorithm.

The remote detection algorithm employed by BioOptoSense is just beginning to enter the marketplace and build a customer base. Thus, it is a good example of a potential benefit. The following section will provide additional examples of how Earth observation data sets are generating concrete value now.

Nanofluidics

The path from basic science investigations to applied application can take many turns. In April 2004, the first Capillary Flow Experiment (CFE) was conducted onboard the ISS to investigate capillary flows and flows of fluids in containers with complex geometries. The work began as fundamental fluid physics investigations led by Mark Weislogel. These investigations led to patents that involve multiphase fluidics in technology applications associated with space exploration such as thermal control systems and liquid fuel tanks. However, the fundamental equations for capillary flow have broad applications in the area of microfluidics. Since then, the ISS has provided a unique venue for exploring the nature of fluidics, leading to dozens of scientific publications and multiple patents.

Dr. Alessandro Grattoni of the Houston Methodist Research Institute (HMRI) spearheaded one set of ISS investigations focusing on using nanofluidics to create a new and novel drug delivery mechanism. Based on research done on the ISS and additional research conducted in his labs, Dr. Grattoni and his team received nearly $4 million from the National Institute of Allergy and Infectious Diseases in 2016 to study a transcutaneously refillable implant that administers pre-exposure prophylaxis drugs to subjects at risk of HIV. The experiment was successfully completed and the implant, which was developed in partnership with Gilead, could be approved for usage as early as 2021.

In 2014 and 2015, Novartis successfully conducted the Rodent Research (RR)-1 and the follow-up RR-2 investigations, which investigated muscle atrophy and bone mineral loss in the microgravity environment. Novartis partnered with HMRI and

…the ISS has provided a unique venue for exploring the nature of fluidics, leading to dozens of scientific publications and multiple patents.

Dr. Grattoni's group to conduct a drug delivery fluidics investigation (RR-6) aboard the ISS in fall of 2017. RR-6 tests the performance of an implantable nanochannel system for delivery of therapeutics that are specifically for muscle atrophy.

Following his two previous investigations onboard the ISS, Dr. Grattoni signed on as one of three principal investigators involved in an ISS experiment on lung tissue titled, The Effect of Microgravity on Stem Cell Mediated Recellularization, which was completed in early 2018. Overall, research conducted by Dr. Grattoni's group at HMRI has led to nine patents and 21 scientific publications, as well as two highly cited literature reviews on nanochannel drug delivery systems. Although many hurdles must be overcome on the road to concrete benefits, the many emerging applications of Dr. Grattoni's work, for which the ISS has served as a catalyst, illustrate how basic research can lead to multiple emerging applications.

The examples above serve to illustrate the breadth of new knowledge generated aboard the space station, and the corresponding potential economic benefits that may be derived. They also illustrate different ways that potential benefits can emerge from research and technology development (R&D) activities onboard the ISS. Fundamental research such as FLEX and CFE generate new knowledge with a broad range of potential uses. Follow-up activities, such as the nanochannel drug delivery work, validate specific applications and demonstrate potential new products. Next, examples of maturing products and concrete benefits arising from potential applications will be discussed.

From Emerging Application to Mature Capabilities: Retrospective Benefits

Although the lion's share of economic benefits derived from the International Space Station (ISS) are still to come, several examples of existing economic impacts have been uncovered. The examples that follow not only illustrate the breadth of these impacts, but also the variety of ways in which economic value both originates and emerges.

Air Filtration

Sometimes it's not the research itself that leads to an immediate benefit, but rather the challenges that must be overcome to conduct the experiment. The Advanced Astroculture (ADVASC) chamber hosted plant research investigations during the first five crew rotations aboard the ISS. As a by-product of their growth process, plants produce ethylene—a gas that accelerates decay. Therefore, a method of removing ethylene from the chamber was required for ADVASC to work. University of Wisconsin at Madison, Wisconsin Center for Space Automation and Robotics, designers of ADVASC, licensed their ethylene-scrubbing technology. This resulted in Airocide, a residential and commercial air purifier capable of removing not only ethylene, but also allergens, bacteria and even viruses. With production capacity for up to 100,000 units in the United States, residential Airocide purifiers can be currently purchased (May, 2018) for $600. Additionally, AiroCide technology has been applied across a spectrum of commercial applications where removing ethylene can improve the shelf life of food products, including more than 100 Napa Valley vineyards, as well as hospitals, commercial markets such as Whole Foods, and food manufacturers such as Kraft Foods and the Coca-Cola Company.

Airocide is an example of a spin-off technology finding beneficial use in multiple markets on Earth. However, it is not the only example of how the technical challenges of conducting research aboard the ISS lead to the development of commercial products. Such technologies have emerged across several fields, including radiation-hardened computer processing and noninvasive temperature monitoring. Xiphos's Q-card processors, which have been demonstrated in multiple uses aboard the ISS since 2004, are used today in industries where equipment takes a beating, whereas Draper's Double-sensor technology is used for noninvasive monitoring of newborn's body temperature in neonatal care products (see the Summaries of Valuation Findings table below for more information).

Sometimes it's not the research itself that leads to an immediate benefit, but rather the challenges that must be overcome to conduct the experiment.

The next example shows how space-based technology can give rise to new sets of goods and services, expanding both the value and number of active participants in the emerging space economy.

Earth Imaging

Started by three NASA engineers in 2010, Planet (Planet Labs, Inc.) provides Earth observation photography from low-Earth orbit (LEO) by using hundreds of small, relatively inexpensive satellites. Beginning in 2013, Planet used the space station as a technology development testbed deploying 110 Earth-imaging satellites, affectionately referred to as "Doves," using the NanoRacks CubeSat Deployer (NRCSD). Their first "flock" of Doves was released in February 2014. The 28 satellites making up this flock were mounted on the JAXA Multi-Purpose Experiment Platform and placed on the Japanese Experimental Module (JEM) airlock slide table for transfer outside the ISS, thus making this effort a truly international collaboration.

Since 2013, Planet has garnered $183.1 million of private funding and secured two contracts with National Geospatial Intelligence Agency worth a combined $34 million. In 2015, Planet acquired BlackBridge, a German company that possessed a five-satellite Earth-imaging constellation called

...the Planet story illustrates how the ISS can provide early access to space, thereby allowing new business models to prove themselves and attract the investment capital needed to truly take off in the marketplace.

RapidEye. In February 2017, Planet acquired Google's Terra Bella, a company possessing a constellation of seven sub-meter imaging satellites. In the same month, Planet launched the largest satellite constellation in history with its Flock3p, which consisted of 88 Earth observation satellites. As of March 2018, Planet operates a fleet of more than 175 satellites and has achieved its original goal of being able to photograph the entire surface of the Earth every day.

With both its technology and business model maturing, Planet now uses commercial launch providers. However, the Planet story illustrates how the ISS can provide early access to space, thereby allowing new business models to prove themselves and attract the investment capital needed to truly take off in the marketplace. As of March 2018, Planet employs more than 470 people, has an estimated annual revenue of $64.4 million, and an estimated value that exceeds $1 billion.

Earth Observation Data

For much of the world, real-time information on hazardous weather, such as tropical cyclones (i.e., hurricanes and typhoons) is not available. Earth imaging supplied by instruments on the ISS can provide real-time data to researchers, meteorologists and disaster response authorities here on the ground.

Since 2014, Visidyne, Inc. has demonstrated the feasibility of studying powerful tropical cyclones from space by measuring the altitudes of the cloud tops within the eyewall, the region of extreme winds and torrential rainfall that lies just outside the cloud-free eye at the center of a tropical cyclone. The Cyclone Intensity Measurements from the ISS (CyMISS) investigation does not require any new instruments to be installed on the ISS, or the development of any novel sensor technologies. Instead, imagery is gathered by simply aiming a camera that is mounted within the Cupola—the dome-shaped Earth observatory of the ISS.

Although small ground-based systems such as hurricane-hunting aircraft are capable of gathering storm data, a benefit of using the ISS to gather measurements on storm and weather systems is that monitoring from space is safer, less expensive, and potentially more effective than ground observation.

In addition to the CyMISS investigation, another instrument aboard the ISS has generated data on wind speeds and wind directions over oceans around the world. From September 2014 through August 2016, the U.S. Navy, the National Oceanic and Atmospheric Administration (NOAA), and European and Indian scientists used the ISS-RapidScat measurements in near real-time to improve weather forecast models (including those used for storm events).

By improving the accuracy of weather modeling and storm track prediction, these Earth observation data sets provide concrete benefits—both economic and quality of life. However, these benefits are difficult to quantify or to separate from the many other sources of information that are used in weather modeling.

Another pathway in which ISS benefits emerge in this focus area is through the maturation of Earth observation technologies and analysis methods. Once confirmed or demonstrated on the space station, new sensors, technologies, and methods of data analysis lead to better capabilities in other satellites and Earth observing platforms. The CyMISS example above illustrates this pathway, as well. Building on the success of the project on the ISS, Visidyne has formed a new commercial company: Trans World Analytics, Inc. (TWAI). TWAI plans to use high-altitude, solar-powered vehicles and microsatellites to collect the data needed to characterize tropical cyclone eyewall clouds and measure storm intensities, with the goal of achieving

Earth imaging supplied by instruments on the ISS can provide real-time data to researchers, meteorologists and disaster response authorities here on the ground.

lifesaving advancements in global knowledge about these devastating storms. If successful, TWAI will be another company (such as Planet) that benefitted from the ISS by demonstrating its technology and validating its business model.

In the area of Earth observation, an additional benefit of note in using the ISS to gather atmospheric and other Earth observation data—both with programmed instruments and crew-operated hardware such as cameras—is the inclusion of the human element to the decision-making process. Space station crews can observe and collect camera images of events as they unfold, while also providing key inputs to ground controllers for the scheduled programmed observations conducted by the automated sensing instruments. This flexibility is an advantage over robotic spacecraft such as traditional weather satellites, especially in the face of unexpected natural events such as volcanic eruptions and earthquakes.

Protein Crystal Growth

As discussed in the previous section, the majority of the economic benefits to be derived from PCG research are still prospective in nature. However, one example from the earliest days of space station assembly illustrates why pharmaceutical companies are so interested in conducting PCG experiments in microgravity.

Beginning in 2001, Amgen utilized the microgravity environment during several space shuttle missions to the ISS to test three drugs. This research, along with further work on the ground, led Amgen to pursue clinical trials that resulted in the U.S. Food and Drug Administration (FDA) 2010 approval of the company's osteoporosis drug, Denosumab (brand name Prolia). In Phase 3 trials, patients receiving Prolia showed a 68% reduction in vertebral fractures, a 40% reduction in hip fractures, a 20% reduction in nonvertebral fractures, and a significant increase in bone density at all sites measured. In 2017, Prolia was reported as the market leader in bone-health treatment with more than 850,000 active patients, representing a 20% market share. Revenues exceeded $1.6 billion in 2016 and $1.9 billion in 2017—an increase of about 20%.

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Robotic Surgery

Launched in 1981 as the product of an international agreement between the Canadian National Research Council and NASA, the space shuttle's Canadarm (Shuttle Remote Manipulator System) provided an adept, robotic manipulation system for maneuvering payloads, satellites and astronauts during space shuttle missions. Later, the exceptional performance capabilities of Canadarm and Canadarm2 (the space station's robotic arm) were instrumental in the assembly of the ISS. Today, Canadarm2, Dextre (Special Purpose Dexterous Manipulator) and the Mobile Base, which is a moveable work platform and storage facility, comprise the Mobile Servicing System of the ISS, and play a critical role in ensuring the safety of the space station and its crew. As indicated in the Canadian Space Agency (CSA) partner perspective below, the technological foundations of Canadarm and its successors have fortified Canada as a technology leader in the development of precision advanced robotic systems. In addition, they have enabled the adaptation of innovations in space robotics to provide technologies for control and situational awareness in surgical robotics.

In 2002, Dr. Garnette Sutherland and his team at the University of Calgary began working with engineers at MacDonald, Dettwiler and Associates (MDA), a Maxar Technologies company, to solve challenges involved in linking high-resolution imaging with robotics to manipulate interventional devices in the operating room. In 2006, a patent was granted for neuroArm. The neuroArm allowed surgeons to conduct robotic surgery while using an MRI. Intraoperative MRI helps surgeons distinguish the otherwise imperceptible edges of tumors, and facilitates the safe removal of all malignant tissue.

The application of MDA's robotic expertise toward NeuroArm and Synaptive's Modus V technology illustrate how ISS technology development can lead to both commercialization and quality-of-life benefits today.

From 2006 through 2017, work on this system resulted in eight patents, 10 scientific articles, and generated more than $18 million in research funding for NeuroArm Surgical. In 2010, IMRIS acquired the NeuroArm technology for $8.3 million. A second-generation model, SYMBIS, successfully received FDA 510(k) clearance in 2015 for brain biopsy procedures following successful clinical trials. Unfortunately, IMRIS filed for bankruptcy in 2015, was acquired by Deerfield Management and rebranded as IMRIS, Deerfield Imaging. The new company has no known plans for commercializing SYMBIS. However, neuroArm/SYMBIS systems were successfully used in 70 surgical cases with varying pathology. In addition, MDA has continued to develop robotic technologies based on their ISS-honed expertise.

In 2013, MDA began a collaboration with Synaptive Medical to develop high-resolution digital microscopes that incorporate robotic arm technology. Synaptive then implemented the robotically operated microscope technology, Modus V, into their BrightMatter surgical platform. Modus V was unveiled in October 2017 as part of the BrightMatter surgical platform.

Most recently, MDA worked with Dr. Mehran Anvari of the Canadian Centre for Surgical Invention and Innovation to develop the Image Guided Autonomous Robot (IGAR) device. IGAR is an emerging robotic solution with many potential applications—the first of which will enable radiologists to remotely conduct MRI guided biopsies of cancerous breast tissues. IGAR-Breast has already completed Phase I & II clinical trials. It holds the potential to become the first FDA 510(k) approved MRI-guided robotic breast biopsy device, and is expected to first demonstrate its capabilities in U.S. markets.

The application of MDA's robotic expertise toward NeuroArm and Synaptive's Modus V technology illustrate how ISS technology development can lead to both commercialization and quality-of-life benefits today. The potential of the IGAR device illustrates further emerging value toward the promise of autonomous robotic surgical capabilities in the future.

The Emerging Commercial Marketplace in Low-Earth Orbit

The global space marketplace has evolved and grown over the past decade. From a valuation of $176 billion in 2006, the global space marketplace has expanded to an estimate exceeding $345 billion in 2018. Perhaps the clearest illustration of the expanding interests of the private sector in space endeavors is the growth in venture capital investments over the past 2 decades. Consider that from 2000 through 2014, space start-ups received a total of $1.1 billion in venture capital investments, or roughly $73 million per year. In 2015 alone, more than $1.8 billion in venture capital investments were made. In 2016, more than 100 investors contributed $2.8 billion into 43 space-related start-up companies in 49 deals, with an average deal size of $57.1 million. In 2017, more than 120 investors contributed $3.9 billion into commercial space companies—an investment increase of nearly 40% within one year.

The ISS, and changes in contracting mechanisms associated with the ISS, have played a significant role in nurturing the emerging space economy. Since 2006, procurement policies for the ISS have shifted away from the traditional cost-plus approach to one that employs a pay-for-performance framework whenever possible. The resulting dynamic has helped generate an influx of venture capital and an increasing number of start-up private space endeavors.

One of the changes credited with improving cost-efficiency, while also promoting the growth of new, privately owned space companies and stimulating greater competition in the space launch market, is a transition in procurement philosophy from “cost-plus” contracts to “fixed-cost” contracts. Cost-plus refers to an arrangement where a contractor is paid for the expenses incurred, along with an additional payment to provide profit. Cost-plus procurements are appropriate when the level of effort required is unknown. For example, NASA has traditionally used cost-plus-based contract structures to design and develop new space capabilities, including the space shuttle, the Space Launch System, and recently the Orion multipurpose crew vehicle. However, cost-plus becomes impractical once preliminary exploration, studies and risk reduction have indicated a high degree of probability that the development is achievable, or when reasonably firm performance objectives and schedules can be established.

In contrast to cost-plus structures where most of the cost, schedule and outcome risks are borne by the government, fixed-cost procurement contracts shift many of the risks toward the contractor. With fixed-cost procurements, the contractor receives a pre-negotiated (i.e., fixed) value regardless of incurred expenses. Shifting cost responsibility to the contractor provides a positive profit incentive for cost and performance control, motivates the contractor to meet milestones, and allows for fair and reasonable price negotiation at the outset.

Increased use of fixed-cost contracts represents significant progress toward a market-based space economy. Employing a procurement philosophy that encourages more public-private partnership is another way in which the ISS partner countries are using the ISS as a catalyst for expansion of commercial interests in space—both encouraging and shaping the way the LEO economy is perceived and accessed by commercial interests.

As part of the economic valuation effort used to generate the valuation summaries provided in this section, three broad areas of International Space Station (ISS) impact on the emerging space economy were investigated: space access, commercial research facilities, and the proliferation of small satellites. Positive impacts to the space launch market, reduction in cost of conducting research and proliferation of commercial facilities and capabilities available on the ISS are discussed below.

Space Access

The commercial launch market has benefitted from changes in contracting mechanisms, discussed previously, intended to promote affordable, reliable access to space with the ISS as just one of many customers. In 2006, NASA initiated the Commercial Orbital Transportation Services (COTS) program and in 2008 the Commercial Resupply Services (CRS) program. The COTS program was designed as a demonstration of a public-private partnership model using a fixed-price, pay-for-performance structure.

The results have been positive. Both SpaceX and Orbital (now Northrop Grumman Innovation Systems), the two initial commercial transportation providers, financed over half of the development costs for their systems. All told, NASA invested approximately $700 million while its commercial partners invested approximately $1 billion, meaning the private sector outspent the public sector in developing new space launch capabilities. Using internal cost estimates, NASA's cost for developing the SpaceX launch vehicle and capsule alone would have approached $4 billion.

As an additional benefit, the published commercial launch cost to lift a pound of cargo to LEO has fallen significantly from early 2000's levels of $8,000-$10,000 per pound. As of July 2018, SpaceX advertises the standard cost for its Falcon 9 launch services at $62 million, with a maximum payload capability of 50,265 pounds to LEO. Using these figures, the Falcon 9 cost-per-pound to LEO is approximately $1,200. The Falcon Heavy, at $90 million and 140,660 lbs, would cost under $700 per pound to LEO. This reduction in cost-to-orbit opens the door for more participation in the space marketplace, thereby increasing the likelihood for space tourism, space-manufacturing and other new services to make a realistic business case for sustained profitability.

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Results to date indicate that both COTS and CRS have had the intended positive impact to the space launch marketplace. Advances in the commercial sector's ability to provide cargo and crew transportation services to LEO have included increased capabilities for both large and small payloads, and an increasing number of options in launch providers. Both companies involved directly in providing launch services for ISS resupply missions as of 2018 have gained significant market share. SpaceX is reportedly the fourth most valuable privately held technology company in the United States, growing from a $100 million investment in 2002 to a valuation of more than $27 billion in 2018. From 2006 to 2013, Orbital Sciences Corporation annual revenues nearly doubled, reaching $1.37 billion in 2013. After merging with Alliant Techsystems to form Orbital ATK in 2015, Orbital ATK was purchased by Northrop Grumman in 2018 for $7.8 billion and rebranded as Northrop Grumman Innovation Systems.

Commercial Research, Research Facilities and Integration Services

The research environment in LEO has evolved over the past decade from one that almost solely involved government funding and operations to one that involves a variety of players. The ISS has contributed to this trend by hosting commercial research and commercially operated research facilities. In addition, recent contracts allow for commercial payload and integration providers.

As highlighted in the partner perspectives to follow, commercialization objectives are diverse, with some of the most important being to drive future revenues, market/segment growth, higher levels of employment, and new innovation pathways. Commercial research is fundamental to achieving these objectives. Processes are in place to aggressively target, monitor and manage lab capacity to ensure the ISS maximizes the impact it has on economic, social and innovation outcomes.

The evolution in the management structure for the U.S. segment of the ISS exemplifies this focus on commercial research. In 2005, the U.S. segment of the ISS was designated as a U.S. National Laboratory to maximize its use by other federal agencies and the private sector. In addition to the shift in procurement philosophy discussed previously, this led to NASA's partnership with an independent organization, the Center for the Advancement of Science in Space (CASIS), to manage the ISS National Laboratory. Under this arrangement, the ISS National Laboratory

is allocated 50% of NASA's ISS resources with the goal of maximizing commercial and private research conducted on the space station. Between 2012 and 2017, they selected 190 investigations to be carried out on the ISS; of these, 56% were commercially sponsored, 42% were academic/nonprofit sponsored, and only 2% were government sponsored.

The results of the efforts of all partners toward commercial research and partnership can be seen in the findings documented in the table below. Many of the most mature benefits listed were derived from early collaborative public-private partnerships including Aquaporin water purification technology, Aerocide air-scrubbing technology and Aerocrine's exhaled nitric oxide monitors. In addition, commercial research from pharmaceutical companies have led to the osteoporosis drug Denosumab (Prolia). As discussed in the Japanese partner perspective, pharmaceutical companies' interest in ISS research continues to grow. Ongoing and planned testing has the potential to impact a wide range of treatments and even demonstrate the effectiveness of new drug delivery systems.

As the demand for space research and development projects increases, numerous commercial companies are developing, operating and maintaining their own commercial payload facilities, both internally and externally on the ISS. To date, 15 commercial research facilities and instruments have greatly increased the breadth of research supported by the ISS, with the majority becoming available since 2014. Currently AlphaSpace, BioServe, Made In Space, NanoRacks, Space Tango, StaARS, TechShot, and Teledyne Brown Engineering are providing ISS research facilities. As mentioned in their partner perspective below, the first European Space Agency (ESA)-sponsored commercial facility, ICECUBES, began operations in 2018. A listing of all commercial facilities available as of June 2018, and a brief description of their capabilities, can be found in ISS Commercial Research Providers table at the end of this section.

These commercial organizations operate their facilities and provide users with more choices to address unique research needs than were previously available. Many of these companies have used their own resources to invest in on-orbit facilities, thereby reducing the risk to the ISS research partner agencies to develop these facilities and services themselves. These companies find customers through the ISS partners, the ISS National Laboratory and their own business development efforts. As commercial facilities hosting ISS research have proliferated, the cost of conducting that research in orbit has dropped by a factor of three. The combination of increased capacity and decreased cost has improved accessibility of space station research to new user groups such as academic institutions and educational non-profits, thereby allowing graduate and undergraduate students to participate in space-based research, as well as to secondary and primary school students to experience space-based research.

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In less than a decade after assembly completion, the ISS has become a fully functioning laboratory where commercial entities routinely carry out research and technology development (R&D) in fields important to their competitive differentiation. Another area in which the ISS is contributing to the development of the space economy is payload integration. The Research, Engineering, Mission and Integration Services (REMIS) contract is another example of the transition in ISS procurement philosophy to emphasize public-private partnerships. This contract was awarded to 16 contractors in September 2017. This move signals a transition from a model where NASA provides its own payload integration, engineering development and sustaining services to one where those services can be purchased from one of many commercial providers through a competitive process. The REMIS contract was developed to allow companies to slowly take over historically governmental functions in a step-wise manner using their commercial approaches to doing business.

The ISS is not a traditional asset where concepts such as return on investment (ROI), payback period or risk-adjusted return are easily applied. By allowing industry to take over payload integration functions as well as own and manage research facilities, the ISS serves as a technology-transfer conduit for the "how-to" experience companies will need to expand their activities in space. At the same time, competition between companies often generates more efficient approaches leading to price reductions, further reducing the costs of doing business in space.

With time, the ISS will give companies the experience they need to think more holistically and confidently about conducting business in space.

International Space Station Role in Small Satellite Market Development

The modern small satellite (SmallSat) revolution began in the 1990s with advances in low-power, highly integrated and lightweight microelectronics. CubeSats are small satellites designed to specific standards. One CubeSat unit is 10 x 10 x 10 cm (4 x 4 x 4 inches), which have come to represent 87% of all SmallSats launched as of 2017. SmallSats offer many advantages over their large, conventional counterparts, including simplified development, relative ease of construction and testing, and lower launch costs. Collectively, the ISS Program's actions and initiatives have had the effect of enabling and accelerating the emergence of a market based on SmallSat technology.

Direct ISS involvement with SmallSats began in 2012, when the Japan Aerospace Exploration Agency (JAXA) deployed the first five CubeSat investigations via the Japanese Experiment Module Small Satellite Orbital Deployer (J-SSOD). In 2013, NanoRacks, LLC became the first commercial entity to utilize the ISS as a platform for CubeSat deployment using the J-SSOD. In cooperation with JAXA and NASA, NanoRacks developed, tested and launched the NanoRacks CubeSat Deployer (NRCSD) in 2014. Between 2014 and 2017, NanoRacks deployed 176 CubeSats using NRCSD, thereby demonstrating that the market for high-capacity SmallSat deployment is growing.

The significant developments in satellite technologies, as well as the unique availability of the ISS as a testbed and deployment platform for SmallSats, has attracted commercial entities. Examples of the technological "firsts" attempted by commercial entities using CubeSats launched from ISS include the first commercial optical communication downlink system (Analytical Space, Inc.) and the first commercial high-precision small satellite orientation and control system (Blue Canyon Technologies). Examples of other technology demonstrations include the first utilization of a radar instrument on a CubeSat, the first CubeSat to de-orbit itself using an inflatable balloon, and the first CubeSat to employ a new hybrid (dual-purpose) antenna and solar power system.

Use of the space station to mature technologies has helped trigger rapid growth in the numbers of CubeSats deployed. At the time the space station launched its first batch in 2012, only 23 launches were documented for the entire year. However, from 2012 to 2017, more than 725 CubeSats were launched with the launch rate growing by 66% annually over this period.

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As discussed previously, Planet is one commercial success story that illustrates how the ISS can provide early access to space, allowing new business models to prove themselves and attract the investment capital needed to truly take off in the marketplace. From 2013 through 2016, Planet used the space station to validate its business model. Planet was able to enter the marketplace 2 years earlier than planned by demonstrating its ability to provide snapshots of the Earth at a useful resolution of 3 to 5 meters (10 to 16 feet) on a daily basis using a fleet of CubeSats deployed from the ISS. In 2018, with an estimated annual revenue of $64.4 million and value exceeding $1 billion, Planet currently operates a fleet of more than 175 satellites and employs more than 470 people.

Planet no longer utilizes the ISS, having moved to commercial launch providers to expand its services and constellation of satellites. Not only has the Earth-imaging technology matured, the business model has proven viable without further ISS involvement. A new market for medium resolution photography from LEO is quickly developing.

Where SmallSats were once the exclusive domain of research institutes and universities, today, 51% of SmallSats are being developed by the private sector and 67% of all SmallSats are developed to provide commercial services. ISS-based deployment helped demonstrate the potential uses of SmallSats and generate interest from the private sector. In that sense, the ISS performed its mission well—to be an innovator and a locus for experimentation and an incubator encouraging economic growth.

International Space Station Partner Perspectives

The following perspectives were provided by the international partner organizations as well as the ISS U.S. National Laboratory. Themes captured in the NASA perspective are taken from the ISS Transition report presented to congress in March 2018.

The ISS is at an important juncture in its history. Benefits of research and technology development (R&D) activities, in terms of economic growth and quality-of-life improvements, are emerging. At the same time, the apparatus and policy frameworks put in place to drive low-Earth orbit (LEO) market innovation are beginning to gain traction. New companies are stepping forward to test their understanding of space and how that environment can further their business interests. However, while a space-based economy appears to be developing, more time is required to realize the full benefits of the ISS and for a truly self-sustaining marketplace to mature. In the partner perspectives that follow, it is apparent that the ISS partners recognize this reality and continue to support ISS research endeavors and commercialization goals for the foreseeable future.

Canadian Space Agency

Canadians understand that bold, ambitious goals in space are powerful drivers of innovation and economic growth, and that space has the power to unite and inspire. Our experience in space started with a vision and imperative to connect all Canadians across a vast territory. To achieve this, Canada became the third country to have a satellite in space with Alouette 1 in 1962. Ten years later, Anik A became the world's first domestic communications satellite system to use a geosynchronous orbit. This demonstrated how sustained efforts and investments in space lead to major advancements in our daily lives, on a national scale.

Witnessing the first humans in space spurred Canadians' imagination, drive for exploration and ingenuity. The development of the original Canadarm for the space shuttle proved to be a transformative project that captivated the public and inspired national pride in our country's technological achievements. In return, Canadian astronauts were able to fly onboard the space shuttle and perform science experiments in microgravity. Their example motivated a generation of young Canadians to aspire to bold dreams, push their limits, embrace science, technology, engineering and mathematics (STEM) and pursue space endeavors.

Building on this heritage, Canada joined the ISS Program in 1988. This formidable enterprise resonated with our country's experience, culture and core values. It represented an expansion, on a global scale, of our foundational aspirations for space exploration—to unite, inspire and catalyze scientific and technological prowess for the benefit of everyone. It mobilized our leading-edge space robotic expertise to build an emblematic contribution for the ISS: the Mobile Servicing System, comprised of the Mobile Base, Canadarm2 and Dextre. This sophisticated system was instrumental in assembling the space station, module by module. Today, Canada continues to perform essential robotic maintenance and operations on the ISS and contribute to the advancement of science by conducting groundbreaking research onboard. On that front, our efforts are strategically focused on human research to enable longer human spaceflight in deep space while maximizing terrestrial benefits.

Canadians understand that bold, ambitious goals in space are powerful drivers of innovation and economic growth, and that space has the power to unite and inspire.

The ISS Program is a success story of international collaboration. For Canada, returns on investments in space exploration are incommensurable. Traditional economic measures fail to fully quantify the benefits, which unfold over decades and permeate across multiple sectors of activity and value chains. However, traditional economic indicators such as export revenues, number of jobs in the space sector, and

number of highly qualified personnel trained show that transfer of know-how and technology from space exploration results in economic growth, positions stakeholders in the space sector to seize opportunities, opens new markets, and creates quality jobs and wealth for Canadians. Furthermore, Canada's participation in the ISS Program has an unparalleled power to inspire and engage Canadian youth in STEM, thus strengthening science culture and literacy, improving employment in high-quality jobs and ultimately growing the economy. The Canadian Space Agency's (CSA's) participation in the ISS program also contributes to the improvement of life on Earth, as scientific discoveries and technologies, developed using the ISS, advance knowledge of human health, and contribute to resolving the challenges we face on Earth.

In 2016, Canada confirmed that it will continue to be a partner in the ISS Program until the end of 2024. The CSA will soon propose options to the Canadian government to pursue our engagement in human exploration after 2024 and participate in future initiatives with the ambition to be a key player in the international efforts to explore deep space and to open the space frontier to humanity.

European Space Agency

LEO offers unique conditions for science and technology research and, as such, remains an exploration destination of utmost interest for Europe. The European Space Agency's (ESA's) Space 4.0 strategy aims to transition LEO activities from focusing on operating the ISS as a government-run laboratory to stimulating a vibrant LEO economy and providing added value services to ESA and other institutional and private sector actors.

Therefore, while ISS operations continue, ESA is taking concrete steps to implement commercial partnerships solicited through a permanently open call. The partnerships aim at providing complementary ISS capabilities and services that benefit the European science community while diversifying and growing the ISS user community. Resulting from the first such partnership, ICE Cubes is the first European commercial facility to conduct research inside ESA's Columbus laboratory. Launched in May 2018, the service provides rapid and simplified access to the space station on a commercial basis while also allowing users to interact with their experiment directly. In 2019, a second partnership—the versatile Bartolomeo commercial all-in-one mission service—will provide end-to-end access for external payloads on the space station for many mission types at competitive prices. It offers an unobstructed view of Earth, direct control of the experiments from the ground via a high-speed data feed, and the possibility of retrieving samples.

Commercial partnerships stimulate private sector engagement in space exploration and foster innovative and inspiring approaches. These services strengthen the competitiveness of the space and non-space industrial base, stimulate R&D, and infuse innovative solutions within ESA space exploration missions. To further nurture commercial research and applications in space, ESA is soliciting proposals for industry-driven research, jointly implemented by the European Exploration Envelope Programme and the ESA Business Applications Programme. The selection process will include assessment of market potential. Research projects that are selected will be implemented in a stepwise manner, with a final phase aimed at demonstrating the ability to successfully introduce a new commercial service or product.

ESA is also organizing the Space Exploration Masters to support innovation and commercially driven applications. This competition takes place annually with strong world-class partners bridging space and non-space sectors. It includes a variety of challenges aimed to foster commercial ISS utilization and engagement of start-ups in future exploration activities. The challenges of the 2018 edition include ideas that are stimulating innovative continuous applications, energy provision, life support systems, biological functions, plant germination processes, resources utilization, material exploitation processes, detection and measurement, etc., for the purposes of space exploration.

Commercial partnerships stimulate private sector engagement in space exploration and foster innovative and inspiring approaches.

Italian Space Agency

From an economic standpoint, this is a transitional time in LEO. The private sector is realizing the market potential and continues to innovate as new companies establish a presence. The Italian Space Agency (ASI) considers technology transfer essential to foster the development of new value-added services and

The ISS, with its associated benefits, is an outstanding catalyst for technology transfer.

obtain growth opportunities in the future of LEO that are offered by the Space Economy. The ISS, with its associated benefits, is an outstanding catalyst for technology transfer. Italy played a significant role in building the space station, and ASI has continued to play an important role in the development and utilization of the ISS. In doing so, Italy has gained significant experience, expertise and knowledge in various fields—i.e., biology and biotechnology, human research, physical science, technology development and demonstration—all resulting in benefits to society at large. The ISSpresso, a multifunctional device that can be used to brew coffee aboard the ISS, exemplified this by providing fundamental insights into capillary flow in microgravity. This payload is the result of a public-private partnership, and provides a good example of how the ASI has succeeded in promoting interest in space through wholly private efforts.

Technology transfer entails the economic valorization of knowledge. The ASI encourages technology transfer by promoting the dissemination of knowledge gained aboard the ISS. The utilization of this knowledge and the subsequent creation of partnerships furthers the synergies among research institutes, subject-matter experts and industries. As an example, in 2015, ASI signed a Framework Agreement of cooperation with the Hypatia Consortium, thus creating the Laboratory for Key Enabling Technologies at its own headquarters. This partnership evolved into the Amaldi Foundation. The Amaldi Foundation will focus expertise in the enabling technologies sector at the national level, and become a national reference point for technology transfer. The ultimate objective is to promote the innovation of business in sectors other than that of space, thereby contributing to the process of economic development and to Italian competitiveness through cooperation between scientific structures and businesses. That stated, ASI continues to envisage the use of the ISS as the unique platform that will gain humankind the appropriate knowledge to access beyond LEO destinations. ASI is emphasizing the role of ISS for human exploration in the national scientific and technological perspective of space research; accordingly, research opportunities are being published with a specific focus on the potential that the proposed researches may have for human exploration beyond LEO.

Japan Aerospace Exploration Agency

The Japan Aerospace Exploration Agency (JAXA) has promoted diverse use of the ISS Kibo module to maximize the broad benefits for the Japanese economy, as well as the significant contributions made toward scientific and technological discovery. 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 services for these purposes by 2024. It is expected that the growing number of collaborations between JAXA and user-service providers will fuel the formation of new organizations and groups that independently provide

The JAXA Strategic Plan through 2024.
Image credit: JAXA

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end-users with high-quality utilization services for Kibo facilities. As these partnerships deepen, operational know-how will be passed on and, thus, a new market will be formed.

Commercially, the agency 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, JAXA has invited Asian and Pacific nations to participate in the use of Japanese facilities to promote diverse partnerships utilizing the ISS. For example, a recent agreement with Singapore aims to use the Japanese Experiment Module (JEM) Small Satellite Orbital Deployer (J-SSOD) to launch a Singaporean satellite.

JAXA's focus is on promoting strategic partnerships to commercially establish the Research and Development testbed aboard the Kibo module. One example is a new fee-based agreement with the Japanese drug discovery company, PeptiDream Inc. The agreement increased the number of protein samples from five to 30 over the lifetime of the agreement. JAXA also doubled the launching frequency from twice to four times a year to meet the requirements from PeptiDream and other users. This accelerates 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.

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.

In closing, the sustained use of the ISS and the Japanese Kibo module, to their full extent through 2024 and beyond, shows significant promise for continued scientific, innovative and economic developments.

ROSCOSMOS State Corporation for Space Activities

State Space Corporation ROSCOSMOS (ROSCOSMOS) is enabling the transition of the Russian Segment of the ISS (ISS RS) to focus on the end user. Plans include creating an operating organization to provide ISS RS utilization services to interested ministries, government departments and private companies. A goal, by 2025, is to increase user-funded applied research that is carried out to solve practical problems up to 45% of the total research conducted in the ISS RS. It is expected that expanding cooperation between ROSCOSMOS and an operating organization will promote the formation of new organizations and groups that will focus on attracting end-user funding for targeted work on the ISS RS. All these actions promote the operational expansion of the ISS RS in a variety of research areas while maximizing the impact and economic effect, as well as obtaining significant results in scientific and applied research.

Currently, ROSCOSMOS is focusing its attention on the development of additive technologies in partnership with private companies. ROSCOSMOS is currently developing a new research infrastructure for unique biomedical experiments on the ISS. In particular, as a part of commercial cooperation, three-dimensional (3-D) bioprinting is being developed as an addition

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to the ISS RS scientific equipment. It will enable further international experiments and promote the increased involvement of scientific institutes and private companies that are interested in the formative technology of 3-D bioprinting. With the cooperation of academic and commercial organizations of different countries (e.g., Kazakhstan, United Arab Emirates, Slovenia, etc.), ROSCOSMOS will continue to focus on investigating the effects of LEO on human life support, plants, materials and combustion processes, as well as satellite orbital deployment.

International Space Station U.S. National Laboratory

As the new space economy begins to emerge, the demand for commercial research is growing rapidly via an expanding community of ISS users and commercial service providers. The ISS U.S. National Laboratory is pioneering this future by enabling the growth of both supply and demand. Since its inception in 2011, the selected portfolio has grown to include more than 200 new projects from commercial companies, academic and nonprofit institutions, and non-NASA government agencies. In addition, 70% of the 45 new projects selected in fiscal year 2017 originated from new-to-space customers, and more than 60% originated from commercial entities.

With 14 commercially operated facilities managed by eight partner companies operational as of 2018, a shift from traditional government-operated spaceflight research is well underway. In support of this shift, the ISS National Laboratory has awarded approximately $34 million in grants both to research customers and to commercial service providers. This funding has been leveraged to generate more than $115 million in non-ISS National Laboratory, non-NASA funding from customers, third-party investors and program sponsors. Fortune 500 companies, government agencies and regional incubators have collaborated with the ISS National Laboratory to successfully use the sponsored program model to support space-based R&D targeted toward solving critical, cross-cutting issues. New collaborations with organizations such as Target Corporation complement multiyear collaborations with Boeing, National Science Foundation and National Institutes of Health—bringing the total independent funding committed through ISS National Laboratory-sponsored programs to date to more than $30 million.

The projected value of the ISS National Laboratory portfolio (as of October 2017) exceeded $900 million in incremental revenue, and these projects address established markets of more than $110 billion in estimated value. Additional parameters that indicate positive value to the nation include a projected time-to-market acceleration of 1.5 years and more than 20 new solution pathways (a measure of innovation that can lead to a major advance in knowledge or new intellectual property).

With 14 commercially operated facilities managed by eight partner companies operational as of 2018, a shift from traditional government-operated spaceflight research is well underway.

Collectively, with NASA and International Partners, the ISS National Laboratory is building the necessary infrastructure for a future that includes a sustainable space-based national laboratory, multiple space platforms that are accessible for government and commercial research, and diverse businesses built upon the foundation of a thriving LEO marketplace.

National Aeronautics and Space Administration

On November 2, 2017, NASA marked 17 years of continuous United States human presence in LEO onboard the ISS. Today, roughly one-quarter of the U.S. population only knows a time when Americans have continuously lived and worked in space.

The ISS represents an unparalleled capability in human spaceflight, which is increasing knowledge of engineering and physical sciences, biology, the Earth and the universe.

The ISS represents an unparalleled capability in human spaceflight, which is increasing knowledge of engineering and physical sciences, biology, the Earth and the universe. This knowledge is benefiting life here on Earth and enhancing the competitiveness of U.S. private industry. The research and technology demonstrations onboard the ISS are also providing the foundation for extending human presence beyond LEO, into deep space.

The international partnership created through the ISS Program and its accomplishments are a testament to the aerospace expertise of all nations involved. It is an example of how countries can work together to overcome complex challenges and achieve collaborative goals. Through the efforts of five space agencies that represent the 15 ISS Intergovernmental Agreement signatory nations, more than 100 countries and areas have utilized, or are currently utilizing, the ISS.

Looking forward, our vision for LEO is a sustained commercial space marketplace where NASA is one of many customers. The development of a healthy commercial supplier base for LEO activities is critical to achieving that vision. Today, the ISS 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 ISS. Through initiatives such as the REMIS contract, NASA is transitioning from historically NASA-provided services for tasks such as payload integration to purchasing those services from a variety of commercial suppliers. NASA is also initiating the Commercial LEO Development program to further the development of private on-orbit capabilities beyond what is available today through the ISS.

NASA intends to continue to expand these types of commercial interactions, utilizing more commercial acquisition strategies, and enabling greater commercial use of the ISS by offering its unique capabilities while providing Earth-similar laboratory facilities. Recently, NASA has provided state-of-the-art, real-time capabilities such as quantitative Polymerase Chain Reaction (qPCR), implemented standard laboratory processing techniques, and has enabled the crew to operate as research partners through real-time space-to-ground discussions with researchers. Additional hardware and data capabilities are currently being proposed, including expanded capabilities for additive manufacturing, biofabrication, cell-culture, multi-material 3-D printing, metal casting, computer-controlled milling and tissue engineering.

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 ISS 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 ISS today to allow users to explore new microgravity applications, test new markets, and communicate those success stories to stimulate broader interest in LEO from nontraditional space users.

Summation Valuation Findings

Taken as a whole, the examples presented throughout this section illustrate the many pathways that are possible for the generation of value from the conduct of research and technology development activities in low-Earth orbit (LEO). Even the procurement mechanisms employed can be tailored to maximize the transfer of expertise needed to confidently conduct business in space and encourage economic development.

In the table that follows, examples are provided for the humankind and economic benefits generated by the International Space Station (ISS). Navigant Consulting, Inc. findings were the primary source for these value examples, with the exception of two cases. Details for Amgen and Tropical Cyclone were already available and therefore not assigned to Navigant for analysis. When practical and useful, details of the findings were further vetted through the international partners and commercial entities associated.

The second table provides descriptions of the commercial research facilities on the ISS. The majority of these facilities (14/15) entered service after the assembly of the space station was completed in 2011, with more than half (8/15) coming on-line in the 1.5 years leading up to this publication (2017-2018). Thus, it is important to remember that the cases presented derived from research activities are early-return benefits. As more time passes, and research efforts continue unabated, the number and value of the benefits returned to Earth will continue to grow.

Findings and Providers

The Summaries of Valuation Findings table starting on the next page summarizes the valuation findings available to the authors. The findings presented show how value is derived not only from the planned research, but also from the engineering accomplishments and technology required to operate the space station, perform research, and maintain a safe living environment for the crew.

The ISS Commercial Research Providers table lists some of the key commercially managed research facilities onboard the space station. Information provided indicates the year of operational start-up as well as a brief description of the facility capabilities. A quick perusal of this table illustrates that commercially managed facilities are a recent development, with the first such facility beginning operations in 2010. Also, the fact that three of these facilities came on line in the first half of 2018, literally as this section was being drafted, accurately portrays the ongoing proliferation of such facilities over the next several years.

Summaries of Valuation Findings

(blue = concrete benefits; grey = potential benefits; tan = new knowledge)

Investigation Title	Valuation Summaries
Advanced Astroculture Chamber	To conduct the Advanced Astroculture Chamber (ADVASC) investigations aboard the ISS, engineers needed to solve the challenge of removing ethelyne from the air. Airocide, an air purifier derived from ADVASC ethylene scrubbing technology, has led to the direct investment of $25 million toward development of production capacity of 60,000 to 100,000 residential units in the United States per year (est. retail value $36 - $90 million/yr). Additionally, Airocide technology has found use across a spectrum of commercial applications, including more than 100 Napa Valley vineyards, hospitals, commercial markets such as Whole Foods, and food manufacturers such as Kraft Foods and the Coca-Cola Company. With more than 320 million tons of fruits and vegetables wasted each year, technologies such as Airocide aim to reduce global food waste and provide a new avenue for global consumers to safely preserve their foods for longer periods of time.
Airway Monitoring	Monitoring technology initially developed to measure the fractionally exhaled nitric oxide (FeNO) content produced by astronauts has led to a line of commercial devices. Aerocrine's NIOX MINO has been used to complete more than 10 million tests since 2004, whereas NIOX VERO was introduced in 2014. In 2015, Circassia Pharmaceuticals acquired Aerocrine for $214 million. In 2017, these NIOX devices were the leading point-of-care FeNO monitoring products, used to perform approximately 3.6 million tests annually in more than 8,700 locations worldwide, with total sales of $18.4 million in the first 6 months of 2017.
Amgen	Beginning in 2001, Amgen utilized the microgravity environment during several space shuttle missions to the ISS to test three drugs. This research, along with further work on the ground, led Amgen to pursue clinical trials that resulted in the Food and Drug Administration's 2010 approval of the company's osteoporosis drug, Denosumab (brand name Prolia). In Phase 3 trials, patients receiving Prolia showed a 68% reduction in vertebral fractures, a 40% reduction in hip fractures, a 20% reduction in nonvertebral fractures, and a significant increase in bone density at all sites measured. In 2017, Prolia was reported as the market leader in bone-health treatment with more than 850,000 active patients, representing a 20% market share. Revenues in 2016 exceeded $1.6 billion and more than $1.9 billion in 2017—an increase of approximately 20%.
Aqua-Membrane	A European Space Agency-sponsored ISS water recovery investigation has helped the Aquaporin Space Alliance and its parent company commercialize the Aquaporin-Inside technology for ground-based applications. This and other Aquaporin activities has resulted in seven patents and consideration in multiple scientific journals. In 2016, Aquaporin reported $1.35 million in revenue as result of commercializing the Aquaporin-Inside Tap Water Reverse Osmosis module for household purifiers. Their recently developed production facility will be used to launch several more products into the advanced water treatment, food and beverage, and desalination markets. These products include a Brackish Water Reverse Osmosis, Seawater Reverse Osmosis, and Forward Osmosis membranes, which were, as of June 2017, in lab and pilot scale production.

Investigation Title	Valuation Summaries
Biokin-4	A partnership between the European Space Agency and Bioclear resulted in a new biological filter and DNA screening technology being commercialized through a spin-off company, Bioclear Microbial Analysis (BMA). BMA reported assets greater than $500,000 and 7 employees at the end of 2017. BMA was created to focus on the use of this technology in terrestrial applications, including identifying microbial influenced corrosion (MIC). The global market to prevent MIC is $7 billion.
Canadarm2 and Dextre	Synaptive Medical and MacDonald, Dettwiler and Associates (MDA), a Maxar Technologies company, collaborated to engineer the Modus V, a commercially available robot-assisted surgery system designed using principles of the space station's Canadarm2 technology. Currently used in leading healthcare centers, research institutions and community hospitals across North America, the Modus V has the potential to offer brain surgery to patients considered inoperable using other methods, and may potentially improve spinal surgery methods by lowering the risk of complications and by reducing recovery time.
Docking/Birthing	Neptec Design Group Ltd. honed expertise in Triangulation & Light Intensification Detection and Ranging Automated Rendezvous & Docking (TriDAR) technologies in the development of autonomous spacecraft docking sensors and algorithms for the space shuttle, ISS, and the Orbital ATK (now Northrop Grumman Innovation Systems) Cygnus resupply spacecraft. Neptec Design Group is estimated to employ around 100 people with an annual revenue of $10 million. In 2011, a spin-off corporation, Neptec Technologies Corp., which currently employs about 100 and has an annual revenue of up to $10 million, was created to translate technologies such as Light Intensification Detection and Ranging (LiDAR) for terrestrial applications. Neptec Technologies currently offers the OPAL-360 (Obscurant-Penetrating Auto synchronous LiDAR) device—a three-dimensional (3-D) scanner that can work in real time and see through obscurants such as dust, snow or fog. It has found traction in industries such as mining, rail, aeronautics and marine transportation. In 2018, Rolls Royce debuted a sophisticated new "situational awareness system" for marine vessels using Neptec LiDAR technologies to create a 3-D map of the surrounding area for navigation. In July 2018 Neptic Design Group was purchased by MDA, a Maxar Technologies Company for $32 million.
Environmental Control Systems	Founded by researchers behind NASA's Microbial Water Analysis Kit, a major component in the ISS crew healthcare system, mWater is a company focused on providing low-cost test kits and monitoring software in support of the global Water and Sanitation for Health (WASH) initiatives. Based on ISS technology, the mWater testing kit costs $10. Updated through receipt of 70,000 surveys from 150 countries each month, in 2018 mWater has the largest WASH open-access database on the planet. The accompanying mobile applications enable the public to record water quality and map safe water sources. More than 25,000 NGOs, governments, and researchers use the mWater app worldwide including USAID, UNICEF, WHO, and the World Bank Innovation Fund.

Investigation Title	Valuation Summaries
Eye-Tracking Devices	More than 2000 Chronos Eye-Tracking Devices (C-ETD) were sold to clinics/hospitals between 2004 and 2014. Around 30 to 40 leading laboratories for vestibular research and neurology have used, or are still using, the system for performing ground-based studies. During the active marketing phase, the technology accounted for 40% to 60% of company turnover and generated $15 million in turnover overall. Chronos Vision is now developing a new application where the experience from the eye-tracker technique is an important feature that is primarily aimed at eye lens replacement procedures— e.g., during cataract surgery. The primary focus is guided surgery for personalized (toric) lenses, which are an improvement on standard intraocular lenses by taking into account the aspheric nature of the cornea.
Japan Aerospace Exploration Agency Protein Crystal Growth	On the ISS, Japanese scientists crystallized a human prostaglandin D2 synthase-inhibitor (H-PGDS/HQL-79 complex), which plays a critical role in the formation of Duchenne's muscular dystrophy (DMD). This allowed researchers to identify a new molecule,TAS-205, which is considerably more effective than HQL-79 at mitigating the expansion of muscle necrosis in mice and dogs. A Phase I study sponsored by the multinational Taiho Pharmaceutical Corporation verified the new TAS-205 inhibitor to be safe for use in humans. Taiho Pharmaceutical has continued to sponsor research on this new drugTAS-205 candidate and, in October 2017, completed a 24-week Phase II trial with 33 DMD patients.
LusoVu	Augmented reality glasses engineered by LusoSpace to help European Space Agency (ESA) astronauts on the ISS led to a spin-off company, LusoVu. LusoVu's commercially available smart glasses—Eyespeak—are capable of assisting patients who are suffering extreme mobility and communication limitations. Eyespeak has the potential to benefit a proportion of the millions of people per year who have stroke/traumatic brain injury-related dysarthria and associated conditions worldwide. Based on the initial ESA study, LusoSpace has also developed future smart glasses for the consumer market with dimensions and shape similar to sunglasses. LusoSpace now has a partnership with DHL Portugal for implementing augmented reality in logistics. To date, LusoSpace has applied for three patents (one granted to date) for augmented reality technology.
NanoRacks-Planet Labs-Dove	Started by three NASA engineers in 2010, Planet provides Earth observation photography from low-Earth orbit. Using the space station as a technology development testbed, Planet deployed 110 small satellites before moving on to using commercial launch providers. With an estimated annual revenue of $64.4 million, and value of over $1 billion, Planet currently operates a fleet of more than 175 satellites and employs more than 470 people. Since its formation, Planet has garnered $183.1 million of private funding and secured two contracts with National Geospatial Intelligence Agency, worth a combined $34 million.
PK-4	Technical know-how gained during ISS research in the field of cold plasmas has led to the creation of three companies: terraplasma (active in hygiene, medicine, water purification, odor control), terraplasma emission control (active in car exhaust technology) and terraplasma medical (active in wound and skin disease treatment). Terraplasma holds three patents for cold plasma-based dental applications, odor removal, and homogenous plasma production. In addition, terraplasma is the exclusive licensee of seven patent families from the Max Planck Society. Following clinical validation, a small ergonometric hospital treatment device for wound management —SteriPlas—is planned for commercial release in fall 2018. Additional products in development include Plasma Care: a miniaturized wound treatment device that can create plasma from ambient air without using a gas tank.

Investigation Title	Valuation Summaries
Radiation-Tolerant Processors	With 10 employees, and an estimated $4 million in annual revenue, Xiphos Technologies has used the ISS for development and demonstration of its Q-card processors since 2004. From 2000-2016, the company received $666,000 in funding from CSA for the development and commercialization of Q-cards. Two companies have been spun-off from Xiphos Technologies. XipLink, with approximately 25 employees and an estimated annual revenue of $4 million, specializes in the optimization of data transmission over Wide Area Network and satellite links. GHGSat, with 40 employees, received $2.3 million in public funding from Sustainable Development Technology Canada. The GHGSat-D satellite, funded in part by Imperial Oil, Shell, Canadian Natural Resources Limited, and Suncor Energy, launched in 2016. This satellite provides information on greenhouse emissions at targeted locations for its stakeholders. As of June 2018, emissions data had been collected for more than 3,000 sites.
Thermolab	The Thermolab experiment, has produced at least seven scientific publications. The direct line of this German Space Agency(DLR)/European Space Agency-supported research led to the development of a noninvasive core body temperature measurement technology—the Double Sensor. Double Sensor technology accounts for 10 patents and has been incorporated into Tcore—a Dräger Medical product currently used in hospitals for monitoring during surgeries and on intensive care units. The benefit of skin-based temperature monitoring is acutely realized in these areas, where the minute-to-minute changes in core body temperature provide critical information—especially where traditional invasive thermometers may not be accepted or used by care providers.
Twins Study	Biotechnology company KromaTiD was initially funded via two grants, totaling $700,000, sponsored by NASA's Human Research Program. The grants were intended to mature technology for analysis of lymphocytes obtained from astronauts to improve space radiation risk analysis. As part of the validation for its chromosomal inversion technology, the company's chromatid painting system was used in the high-profile NASA ISS twin study in 2015. As of 2018, KromaTiD has raised $8.35 million, been granted three U.S. patents, published four scientific papers, and launched distribution partnerships with Tokyo Future Style and Tebu-Bio in Japan and Europe, respectively.
Vessel Identification System	A partnership between the ISS and the Norwegian Defense Institute led to the installation of Automatic Identification System (AIS) receivers on the ISS. These receivers are capable of receiving data from vessels throughout the ocean in areas that were previously too remote to detect. The extension of the AIS infrastructure, which prior to implementation on the ISS was primarily ground-based and limited to coverage within 15 miles of shore, has led to the proliferation of satellite-based AIS receivers including those onboard the ISS. This space-based expanded coverage facilitated rescue efforts for 24 ships sunk, foundered, grounded or otherwise lost at least 15 nautical miles away from shore in 2017 alone. A total of 310 passengers and crew members were rescued during these incidents.

Investigation Title	Valuation Summaries
Advanced Colloids Experiment-Temperature-6	Procter & Gamble's (P&G's) investigations onboard the ISS have led to three patent applications in 2017, with the potential to impact P&G's sprayable products, including billion-dollar brands. Colloids exist all around us, and include commodities such as air fresheners, milks, foams and hair gels. In addition to increasing our fundamental knowledge of colloidal substances, the Advanced Colloids Experiment (ACE) investigations may lead to longer shelf life as well as lower production and transportation costs worldwide.
Center for the Advancement of Science in Space Protein Crystal Growth	Merck Research Laboratories is performing protein crystal research onboard the ISS to develop a subcutaneous (SC) formulation of the immunotherapy drug Keytruda, which is currently administered intravenously. SC reformulations of similar drugs, such as Herceptin, provided a 44% savings in time and a 77% savings in medical staff effort. Additionally, over 90% of patients preferred the SC formulation due to reduced pain, discomfort and side effects. If the SC reformulation is more stable at room temperature, it will reduce costs associated with storage and transportation. Any of these outcomes will lead to increased market share over competitors.
Hyperspectral Imager for the Coastal Ocean	Using ISS-generated Earth Observation data, Dr. Amin refined remote detection algorithms to identify harmful algal blooms (HABs) and demonstrated their effectiveness. HABs, which the Environmental Protection Agency classifies as a "major environmental problem" in all 50 states, negatively impact tourism and fishing industries across the globe. A spin-off company, BioOptoSense LLC, has been formed to market this detection capability. The BioOptoSense algorithm has already been used by the University of Mississippi, City College of New York, and the Naval Research Laboratory.
ICARUS	The ICARUS initiative, an international scientific collaboration founded in 2002, has developed lightweight transmitters as well as the ICARUS antennae for the ISS to provide greater insights into the large-scale, long-term migratory patterns of animals and insects. The low orbit of the ISS (400 kilometers [249 miles]) offers ICARUS the ability to detect weakly transmitted signals, thus lowering the power and size requirements for transmitters and allowing researchers to track smaller organisms than ever before. To fund the development of small, lightweight transmitters, ICARUS received $23.3 million from the German Aerospace Center, and $2.1 million from the Max Planck Society. The ICARUS antennae was installed on the Russian Segment of the ISS in August of 2018, and will track more than 15 million transmitters—a large improvement from the current limit of 22,000. By enabling the long-term monitoring of animal migratory behaviors, ICARUS may potentially help identify ongoing variations in climate change, as well as provide improved natural disaster preparedness and warning systems.
Made In Space Fiber Optics	In 2016, Made In Space announced plans to begin the commercial manufacturing of high-fidelity optical ZBLAN fibers in space. Unlike those produced on Earth, ZBLAN fibers produced in space develop with far fewer defects, and thus their performance may approach the theoretical limit for signal transmission efficiency. In collaboration with Thorlabs Inc., Made In Space conducted the Optical Fiber Production in Microgravity investigation on the ISS beginning in September 2017 in preparation for large-scale manufacture of high-quality fiber optics in orbit.

Investigation Title	Valuation Summaries
Microfluidics	Medical research conducted by Methodist Hospital Research Institute (MHRI) has led to nine patents and 21 scientific publications, as well as two highly cited literature reviews on nanochannel drug delivery systems. The MHRI research on the ISS has focused on understanding how fluids flow through very small channels (nanofluidics) in order to potentially create drug delivery systems and tunable nanochannel implants. In 2013, the MHRI received $4 million from the National Institute of Allergy and Infectious Diseases to study a refillable implant for administering HIV pre-exposure prophylactics. The implant, developed in partnership with Gilead, may be approved for use as early as 2021. In 2017, MHRI received $2.7 million in research funding from Novartis and the Center for the Advancement of Science in Space to study the use of the nanochannel system in delivering a muscle atrophy drug. Nanofluidics research may influence how medicines are administered across the world, and could provide a new pathway for treating diseases that currently require costly, invasive procedures.
Mobile Servicing System	Translated from the space station's Canadarm2 technology, NeuroArm was a pioneering MRI-compatible surgical robotic system that resulted in eight patents, 10 scientific articles, and more than $18 million in research funding for NeuroArm Surgical Ltd. IMRIS acquired NeuroArm technology for $8.3 million in 2010. A second-generation model, SYMBIS, successfully received Food and Drug Administration 510(k) clearance in 2015 for brain biopsy procedures following successful clinical trials. In 2015, Deerfield Management acquired IMRIS and rebranded the company as IMRIS, Deerfield Imaging. The new company has no known plans for commercializing SYMBIS.
Mobile Servicing System	The Center for Surgical Invention & Innovation (CSii) and MacDonald, Dettwiler and Associates (MDA), a Maxar Technologies company, are collaborating to develop the Image Guided Robot (IGAR) surgical system, which enables the remote manipulation of devices inside an MRI bore. The IGAR underwent Phase II clinical trials in 2015 following the completion of a Phase I clinical trial in Quebec in 2014. In November 2017, the collaboration between Csii and MDA led to the formation of a spin-off company, Insight Medbotics Canada Corporation, to commercially launch IGAR products. One such product, IGAR-Breast, holds the potential to become the first Food and Drug Administration 510(k)-approved MRI-guided robotic breast biopsy device, and is expected to first demonstrate its capabilities in U.S. markets.
SG100 Cloud Computing Payload	Expanding on technology developed for computers used in the Alpha Magnetic Spectrometer-02 (AMS-02) investigation on the ISS, Business Integra (BI) was formed to refine high-performance, radiation-tolerant computers for use in low-Earth orbit, as well as in high-radiation Earth environments. BI's spaceflight-tested SG100 computer achieved NASA's highest technology readiness level (TRL), TRL-9, and boosts processing capabilities by 12-fold at only 40% of the cost of currently available radiation-hardened computers.

Investigation Title	Valuation Summaries
Tropical Cyclone	Since 2014, atmospheric scientists at Visidyne, Inc. have captured time-lapse images of tropical cyclones using automated and handheld cameras aimed through one of the portals on the space station. This imagery is used to measure the heights and temperature of the cloud tops just outside the clear eye at the center of the storm. Combining these measurements with other data allows scientists to retrieve the storm's central sea-level air pressure, which leads to more accurate prediction of the intensities (peak wind speeds) and paths of the storms before they hit land. It also provides an increased understanding of the eyewall replacement cycle. Building on the success of the CyMISS project on the ISS, Visidyne has started a new commercial company called Trans World Analytics, Inc. The company will first use high-altitude, solar-powered vehicles, followed by microsatellites, to characterize tropical cyclone eyewall clouds and measure storm intensities, with the goal of achieving lifesaving advancements in global knowledge about these devastating storms.
FLEX-2	The Flame Extinguishment (FLEX) investigations uncovered a new form of combustion that occurs at a lower temperature than previously observed. Globally, transportation-related emissions account for nearly 23% of energy-related CO_2 emissions. In the U.S. transportation sector, engines account for nearly 50% of all nitrogen oxide emissions and over 66% of particulate matter (soot) emissions. As researchers unravel the mechanisms of this "cool flame," new knowledge may lead to more-efficient, lower-emission liquid combustion engines. As of 2016, the World Health Organization (WHO) estimates that 92% of the world's population lives in areas where the air quality does not meet the WHO's recommended guidelines.
Robonaut	Robonaut 2's nearly 50 patented and patent-pending technologies have potential applications in multiple industries, including logistics and distribution, medical and industrial robotics, and beyond. For example, RoboGlove technologies have the potential to reduce the more than 1 million repetitive motion injuries per year in the manufacturing industry. The economic cost of these injuries is over $19 billion annually in the United States alone.
Robotic Refueling Mission	Intended to advance and demonstrate robotic capabilities involved in the refuel, repair and maintenance of satellites in both near and distant orbits, the Robotic Refueling Mission (RRM) series of investigations hold the potential to revolutionize the way satellites are serviced and refueled. Successful implantation of RRM technology may save the satellite industry between $7.1 and $16.6 billion per year in replacement costs.

ISS Commercial Research Providers

Facility/Company	Description
Additive Manufacturing Facility (2015)/Made In Space	The Additive Manufacturing Facility provides hardware manufacturing services to NASA and U.S. National Laboratory, and was the first commercially available manufacturing service in space. It also provides research opportunities for terrestrial and space-based three-dimensional printing applications.
Bone Densiometer (2014)/ TechShot	The Bone Densitometer (BD) provides a bone density scanning capability on the ISS for utilization by NASA and the ISS U.S. National Laboratory. The BD payload measures bone density using Dual-Energy X-ray Absorptiometry.
Commercial Generic BioProcessing Apparatus (2001)/ BioServe Space Technologies	The Commercial Generic Bioprocessing Apparatus (CGBA) provides programmable, accurate temperature control for applications ranging from cold stowage to customizable incubation. The CGBA is used for experiments on cells, microbes and plants.
DLR Earth Sensing Imaging Spectrometer (2018)/Teledyne Brown Engineering	Attached to the Multiple User System for Earth Sensing (MUSES) platform, which provides power, data-flow and inertial pointing stabilization for up to four instruments, DLR Earth Sensing Imaging Spectrometer (DESIS) is a hyperspectral sensor system with the capability of recording image data using 235 closely arranged channels ranging from the visual to the infrared spectrum (between 400 and 1000 nanometers) with a spatial resolution of 30 meters (98 feet) while in ISS orbit, at an altitude of 400 kilometers (249 miles).
ICECUBES (2018)/Ice Cubes Service	Offers room to run experiments and conduct research in weightlessness inside the European Space Agency's Columbus laboratory on the ISS. It will allow experiments to run for more than 4 months in space. Astronaut time and expert advice come as part of the package.
Made In Space Fiber Optics (2017)/Made In Space	Made In Space Fiber Optics is a miniature fiber-pulling machine that harnesses the microgravity environment to produce optical fiber with fewer defects than those that can be produced on Earth. The fiber optic material chosen for this demonstration is ZBLAN. Research indicates this material has the potential for better optical qualities than the silica used in most fiber optic cable.
Materials International Space Station Experiment Flight Facility (2018)/Alpha Space	Materials International Space Station Experiment Flight Facility (MISSE-FF) is a material research facility externally housed on the ISS that offers testing for atomic oxygen, radiation exposure, vacuum testing, zero gravity and extreme temperatures. The primary MISSE-FF platform provides the ability to test materials, coatings, and components or other larger experiments in the harsh environment of space, which is virtually impossible to do collectively on Earth.

Facility/Company	Description
Multiple User System for Earth Sensing (2017)/Teledyne Brown Engineering	Multiple User System for Earth Sensing (MUSES) is the first multi-user facility on an ISS ExPRESS Logistics Carrier. The facility primarily serves as a platform for Earth-viewing sensors and other technologies that require long-term access to the space environment. The end-user data products generated from the Hosted Payloads flown on MUSES can be used for: Maritime Domain Awareness, Agricultural Awareness, Food Security, Disaster Response, Air Quality, Oil/Gas Exploration, Fire Detection and Heritage Preservation.
Multi-use Variable-g Platform (2017)/Techshot	The commercially developed, owned and operated Techshot Multi-use Variable-g Platform (MVP) includes two internal carousels that simultaneously can produce up to 2 g of artificial gravity. Besides providing artificial gravity, the temperature inside MVP can be controlled between 14°C (57°F) and 40°C (104°F) and humidity maintained between 50% and 80%. Oxygen and CO_2 levels also are monitored and recorded. MVP is used to conduct research in space with a wide variety of sample types, such as fruit flies, flatworms, plants, fish, cells, protein crystals and many others.
NanoRacks Cube Sat Deployer (2013) /NanoRacks, LLC	The NanoRacks CubeSat Deployer accommodates up to six 1U CubeSats, a single 6U CubeSat or a combination of different size satellites totaling up to 6U as dictated by the CubeSat design. CubeSats are preinstalled in launch cases on the ground. Up to eight preloaded 6U launcher systems are deployed per air lock cycle.
NanoRacks External Platform (2017)/NanoRacks, LLC	The NanoRacks External Platform offers exposure to the extreme environment of space and currently supports a variety of research including technology demonstrations, earth and space sensors, and materials exposure. Delivered results include, but are not limited to, data and payload return. The facility is equipped with its own power supply to distribute power to experimental containers. An internal computer system monitors and controls the flow of power to the containers, receives commands from on-ground users, and communicates research data to those users.
NanoRacks Kaber MicroSat Deployer (2015)/NanoRacks, LLC	The NanoRacks Kaber Microsat Deployer is a reusable system that provides command and control for satellite deployments from the ISS. The Kaber enables the deployment of microsatellites up to about 100 kilograms (220 pounds) into space from the ISS. Microsatellites that are compatible with the Kaber have additional power, volume and communications resources enabling missions in low Earth orbit of more scope and sophistication.
NanoRacks Platform 1,2,3 (2010)/NanoRacks, LLC	NanoRacks Platforms is a multipurpose research facility that provides power and data transfer capability to the NanoRacks Modules. Each platform is approximately 43 x 23 x 51 centimeters (17 x 9 x 20 inches) and weighs approximately 5 kilograms (12 pounds). Each platform provides room for up to 16 payloads in the CubeSat form factor to plug into a standard USB connector, which provides both power and data connectivity. Platforms 1 and 2 were installed onboard the ISS in 2010, with Platform 3 installed in late 2013.

Facility/Company	Description
Space Automated Bioproduct Lab (2015)/BioServe Space Technologies	Ultimately, Space Automated Bioproduct Lab (SABL) replaces the two Commercial Generic Bioprocessing Apparatuses that BioServe has had onboard the ISS since 2001. SABL takes advantage of the rear avionics cooling system and water loop heat rejection capabilities of the ISS. In addition, SABL is a front access facility that requires less crew time to access the research volume and also provides enhanced data capabilities.
Space Technology and Advanced Research Systems, Inc.-1 Experiment Facility (2017)/ Space Technology and Advanced Research Systems	Space Technology and Advanced Research Systems, Inc.-1 Experiment Facility (STaARS-1 EF) is a temperature-controlled (18°C [64°F] to 37°C [99°F]) experiment facility that provides the environmental control, power and communication required for efficient and effective biotechnology and life science research on the ISS. STaARS-1 EF supports standard experiment container form factors and next-generation cube labs. The experiment containers can be commanded and controlled in a static rack for microgravity experiments and in a hyper-G centrifuge for Earth analog controls or Martian and lunar gravity simulations. The next-generation cube lab ports provide power and communication for up to a 1.5 U cube lab. The flexibility of operation, including temperature control from 18°C (64°F) to 37°C (99°F) allows STaARS-1 EF to support a diverse suite of microgravity research.
TangoLab 1 & 2 (2016)/ SpaceTango	The TangoLab facilities provide a standardized platform and open architecture for experimental modules called CubeLabs. This reduces development cycle time,cost for research and development and pilot manufacturing using microgravity. The facilities are easily reconfigurable with the associated payload cards and CubeLabs, which are installed on orbit. In 2017, TangoLab-2 was installed onboard the ISS with improved heat rejection capability, thus enabling payloads with greater power draw and lower temperature requirements to use the facility.

Astronaut Peggy Whitson working with the Minus Eighty Laboratory Freezer for ISS 1 Electronics Unit (EU) in the Japanese Experiment Module after failure of the EU.

Image credit: NASA

Scientific Valuation of the International Space Station

Since the launch of the first module, scientific results of the multidisciplinary research and technology activities performed on the International Space Station (ISS)— ranging from groundbreaking DNA amplification in space to analysis of the sun's activity on Earth's climate—have progressed steadily. Examples of a few of the scientific advancements highlighted in this section represent the work of more than 5,000 scientists on Earth, and demonstrate the unprecedented global impacts of the orbiting laboratory.

International Space Station Scientific Value

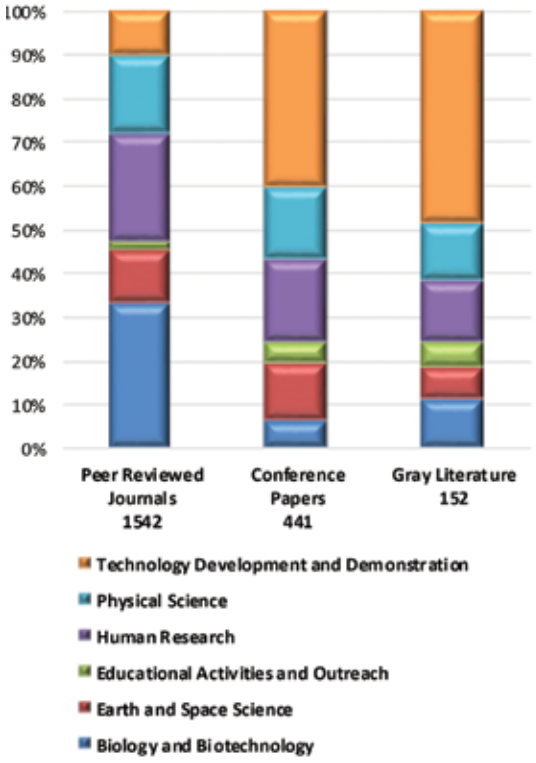
Analyzing ISS scientific impacts is an exceptional challenge because of the unique microgravity environment of the ISS laboratory, the multidisciplinary and international nature of the research, and the significance of the investment in its development. As a result, the ISS Program uses different methods to describe the impacts of ISS research activities. All ISS results publications across the ISS international partnership are continuously updated and posted at http://www.nasa.gov/stationresults.

Publication Metrics from the International Space Station Results

As of May 1, 2018, the ISS Program identified a total of 2,135 publications since 1998 with sources in journals, conferences and gray literature.

One method used to evaluate scientific output from the ISS is to track the article citations and Eigenfactor rankings of journal importance across the ISS partnership. Because different disciplines

ISS Publications Collected Through May 31, 2018



Credit: NASA

ISS Publications in the Top 100 Global Journals, by Eigenfactor

(Eigenfactor Ranking as of 2016-2017 journal rankings)

	Clarivate Analytics® Ranks	Source (# of ISS Articles)
ISS Articles in Top 10 Sources	1	PLOS ONE (42)
	2	Nature (2)
	3	Proceedings of the National Academy of Sciences of the United States of America (4)
	4	Science (3)
	6	Physical Review Letters (32)
	7	Nature Communications (1)
	8	New England Journal of Medicine (1)
ISS Articles in Top 100 Sources	13	Journal of Biological Chemistry (2)
	14	Scientific Reports (21)
	15	The Astrophysical Journal (1)
	17	Chemical Communications (1)
	20	Advanced Materials (1)
	22	Journal of Neuroscience (1)
	35	RSC Advances (1)
	38	Astronomy and Astrophysics (2)
	41	Optics Express (2)
	42	Chemistry - A European Journal (1)
	53	Geophysical Research Letters (4)
	55	NeuroImage (1)
	60	The Journal of Chemical Physics (5)
	70	Physical Review E (2)
	74	Langmuir (3)
	82	Biomaterials (1)
	94	Journal of Clinical Endocrinology and Metabolism (1)

Credit: NASA

have different standards for citation and different time spans across which citations occur, Eigenfactor employs an algorithm that uses the entire Web of Science citation network from Clarivate Analytics (formerly an analytical component of Thomson Reuters). This algorithm spans the previous 5 years to create a metric that evaluates the importance of each journal (**www.eigenfactor.org**).

The Eigenfactor Score counts citations to journals in both the sciences and social sciences, eliminates self-citations of journals, and is intended to reflect the amount of time researchers spend reading the journal. Since the first ISS publication,135 ISS publications have been listed in the top 100 journals by Eigenfactor; 85 of those ISS publications were in the top 10 journals as reported by Clarivate Analytics.

Global Impacts on Science

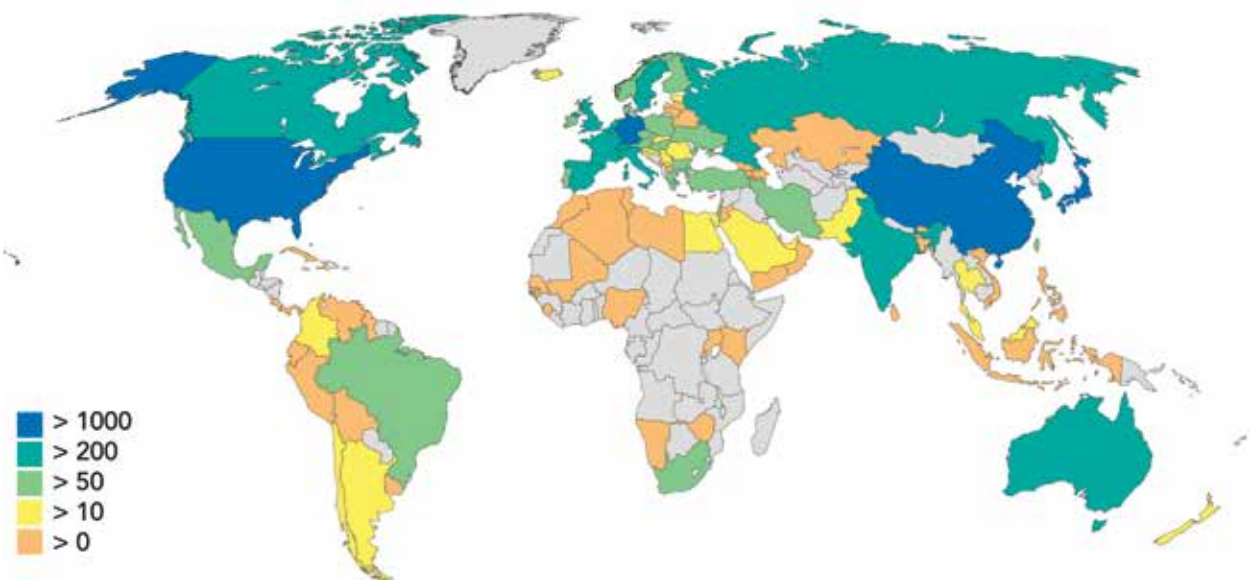
Results from space station research reach beyond international borders, and beyond the countries whose agencies sponsored them. The heat map below provides a global representation of all the countries that have cited the ISS results published in scholarly journals. Such maps illustrate the international reach of ISS publications and their subsequent contributions to scientific literature.

Results from space station research reach beyond international borders, and beyond the countries whose agencies sponsored them.

Following are the top five most-cited results publications from space station research as of May 30, 2018.

The **AMS-02** investigation collected and analyzed billions of cosmic ray events, and identified 9 million of these as electrons or positrons (antimatter), thereby providing data that may lead to the solution of the origin of cosmic rays and antimatter and increase the understanding of how our galaxy was formed. (Aguilar-Benitez M, et al., Physical Review Letters, 2013. Times Cited = 489)

The **Subregional Bone** investigation found that the greatest space-induced bone loss occurs in pelvis, hip, and leg bones, which should be the focus of countermeasures and surface activities designed for space explorers on future missions beyond low-Earth



A heat map of all of the countries whose authors have cited all scientific publications from ISS research.
Image credit: NASA

orbit (LEO). (Lang TF, et al., Journal of Bone and Mineral Research, 2004. Times Cited = 381)

The **Microbe** investigation implicated that the Hfq (RNA chaperone) protein acts as a major post-transcriptional regulator of Salmonella gene expression. (Sittka A, et al., Molecular Microbiology, 2007. Times Cited = 232)

The **Astrovaktsina** investigation showed that the localization of the V-antigen in Yersinia plays a crucial role in the translocation process and its efficacy as the main protective antigen against plague. (Mueller CA, et al., Science, 2005. Times Cited = 231)

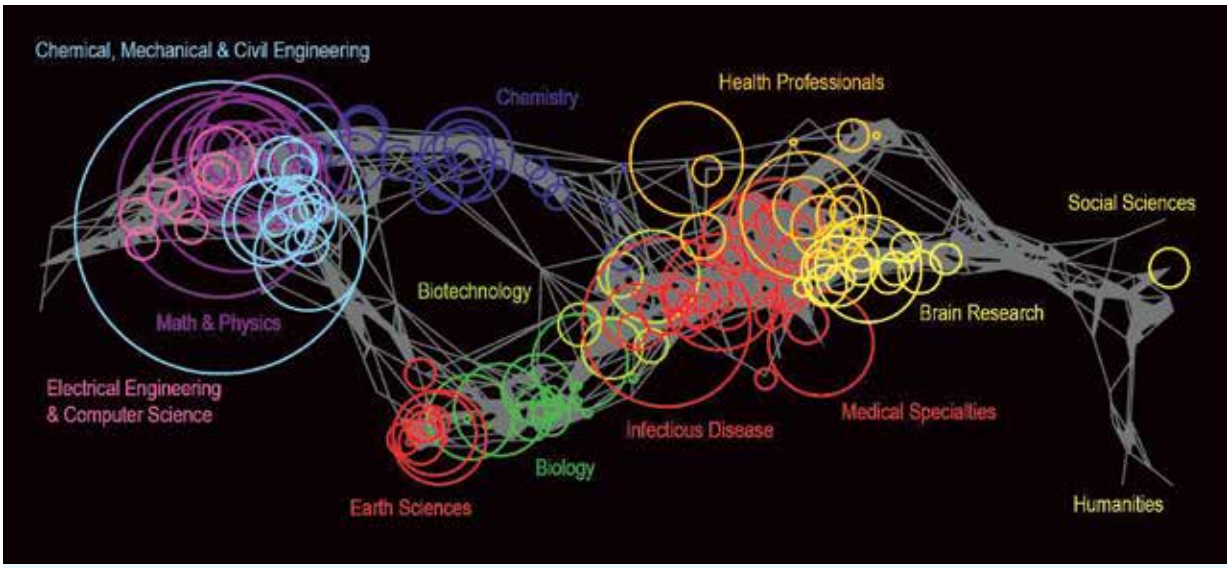
The **Monitor of All-sky X-ray Image** (MAXI), in coordination with the gamma-ray burst satellite Swift (USA), observed the instant that a massive black hole swallowed a star located in the center of a galaxy, 3.9 billion light-years away. This behavior had only been theorized before.This first-ever observation contributes to a better understanding of the current state and evolution of the universe. (Burrows DN, et al., Nature, 2011. Times Cited = 228)

Interdisciplinary Impacts on Science

The ISS Map of Science is a colorful visualization of the spread of knowledge gained from ISS research across the many different disciplines of science. The underlying base map is the widely used disciplinary classification system and layout algorithm known as the University of California, San Diego (UCSD) Map of Science.

> ...the science conducted on the space station has had an impact on 12 of the 13 primary disciplines that comprise the base map of all science...

The UCSD Map of Science is a reference-standard, disciplinary classification system derived from articles and citations contained in more than 25,000 journals carried by Thomson Reuters Web of Science and Scopus. In the UCSD visualization, each article is located within a network of 554 subdisciplines, which are then aggregated into 13 primary disciplinary classifications. Each colorful circle therefore represents a unique subdiscipline and is sized by how many scientific articles are present within that subdiscipline. The UCSD Map of Science was originally produced in 2005 at the request of UCSD, and updated in 2012. Its map and classification system are distributed under



The ISS Map of Science, showing the 12 different scientific disciplines in which space station research has published scientific articles.

Image credit: NASA

Overlaid on the standard UCSD Map of Science framework, and using its algorithm, the ISS Map of Science in the figure below displays the multidisciplinary nature of ISS research, given the significant presence of overlapping colors representing the different disciplines. Most importantly, this ISS Map of Science shows that the science conducted on the space station has had an impact on 12 of the 13 primary disciplines that comprise the base map of all science (Humanities is the exception). These include both space-related and non-space-related scientific disciplines.

Scientific Highlights from the International Space Station

The diverse array of space station research has led to a steady stream of publications among the international partnership that have contributed to the advancement of science across many disciplines. Such results have advanced scientific knowledge in a variety of areas, including physiology, biomedicine, radiation, plant biology, physical sciences, elucidation of space, and observations of Earth. Only the space station can enable access to such a unique laboratory where every variable—including gravity—can be manipulated to lead to new discoveries and new scientific questions.

Physiological Systems

Investigations performed on the space station are designed to study risks to human health that are inherent in space exploration, as well as to advance understandings of health on Earth. These investigations address the mechanisms of the risks of living in space, and also enable the development and testing of countermeasures to reduce these risks. Results from this body of research are critical enablers for missions beyond LEO and also contribute fundamental scientific knowledge in physiological systems.

Animal Studies

Investigations of medaka fish flown in an aquatic habitat on the space station revealed that the mineral density of the upper pharyngeal bone and the tooth region decreased by about 24%, and the osteoclast (i.e., cells that break down bone) volume increased compared to ground control fish. Some genetic changes were found with the brain, eye, liver and intestine, with the intestine being most sensitive to microgravity. Genetic analysis also revealed a significant increase in activity in two genes that may be involved in mitochondria function, thus indicating that osteoclast activation might be linked to the reaction of mitochondria to microgravity. These results suggest that a common regulator of immune and stress response may be exhibited during spaceflight, thereby contributing to the understanding of the mechanisms behind bone density and organ tissue changes in space (Chatani, et al, 2015 and 2016; Murata et al., 2015). In the nematode, *C. elegans*, changes in gene expression associated with energy metabolism and muscle attachment complexes have also been observed when flown to the space station. Specifically, these muscle attachment complexes are associated with a muscle intrinsic repair mechanism, which appears to have relevance to human muscle atrophy (breakdown) with disuse and possibly aging (Honda et al., 2012).

Video screen shot of medaka in the Aquatic Habitat onboard the Kibo.

Image credit: JAXA

Results of mouse research on the space station have shown changes in many physiological systems as a result of living in microgravity. Mice flown on a 17-day mission to the space station exhibited unexpected bone loss in the mandible and skull, which are not the usual load-bearing bones that are most sensitive to bone loss in space (Ghosh 2015). In another study, when mice were centrifuged at 1-gravity (1-g) during their stay on the space station, they maintained muscle and bone mass but exhibited an overall decrease

Results from this body of research are critical enablers for missions beyond LEO and also contribute fundamental scientific knowledge in physiological systems.

in physical fitness and an increase in sensorimotor impairment. These results raise new questions about the role of artificial gravity countermeasures to maintain human health during long-duration exploration-class missions. (Shiba et al., 2017). Studies have also shown that spaceflight activates lipotoxic pathways (i.e., an accumulation of lipid products in cells) in mouse liver, initiates a loss of retinol, and creates a possible increased risk of fatty liver disease, thereby opening new research questions surrounding liver metabolism and function (Jonscher et al., 2016).

In a long-term mouse mission of 91 days, results suggest that the force-producing extensor digitorum longus (EDL) muscle may resist microgravity-induced atrophy by activating certain inherent compensatory and protective pathways (Cancedda et al., 2012). These studies also show an increased sensitivity of the "antigravity" soleus muscle—the muscle responsible for walking and standing activities—adding insight into the mechanisms for resistance of EDL that could contribute to the development of countermeasures to muscle loss in space (Sandonà et al., 2012). Moreover, analysis of specific bone formation and resorption marker expression in these mice suggested that the microgravity-induced bone loss was due to both an increased bone resorption and a decreased bone deposition. More specifically, the protection observed in transgenic mice overexpressing the PTN (pleiotrophin) protein was likely due to higher osteoblast activity, which aids in bone formation (Tavella et al., 2012). In mouse cardiovascular studies, mice flown to the space station for 8 days showed a decreased expression of calcium channels, which regulate the contractibility of smooth muscle cells in portal veins that carry blood to the liver. A similar effect was observed in rat liver portal vein myocytes cultured on the space station for 8 days, as well as in rats during hind-limb suspension on Earth (Dabertrand et al., 2011).

Human Studies

ISS research has revealed astonishing similarities between spaceflight and the aging process through the study of astronauts' heart and blood vessels. Constant elevation in blood pressure in the brain while in space, reduced physical activity, and the constant exposure to higher levels of carbon dioxide (CO_2) might impair the ability of blood vessels of the brain to respond to changes in arterial blood pressure and CO_2. This was accompanied by insulin resistance in some astronauts during spaceflight—an issue that is also observed in the elderly. Walls of the carotid and femoral arteries were found to be significantly thicker (12%) in all astronauts after spaceflight. Increase in artery stiffness and thickness after 6 months on the space station corresponded with 10 to 20 years of normal aging but was reversed within a few days of return. The same pattern was seen in isolation studies (e.g., the Mars 500 study), indicating this may be a stress response to confinement rather than an effect of microgravity (Arbeille et al., 2016; Hughson et al., 2016). One study demonstrated that an improved rebreathing method was a more accurate tool to properly monitor cardiac function during spaceflight than measuring blood pressure at fingertips (Hughson et al., 2017). Further evidence from this study also showed that the elevated CO_2 exposure could be linked to the vision impairment intracranial pressure (VIIP) syndrome (Hughson et al., 2017). Studies of astronauts' core body temperature in microgravity during periods of exercise and rest have shown an increase of 1°C, which is significant enough to impair physical and cognitive performance if not addressed for long-duration exploration missions beyond LEO (Stahn et al., 2017).

ISS crew members report a variety of neurological symptoms that may be related to changes in cerebral venous outflow. Studies on blood flow changes using plethysmography confirm that long-duration spaceflights lead to a redistribution of venous blood volume and show interesting differences in the amplitude of cardiac oscillations measured at the level of the neck veins. Remarkably, the proposed portable system is able to detect cross-sectional area variations of neck veins with enough sensitivity to be useful for studies concerning cardiac oscillations (Taibi et al., 2017).

Research has shown that 60% of long-duration astronauts (versus 29% of short-duration astronauts) experienced a significant decrease in eyesight postflight (i.e., spaceflight-induced ocular syndrome), accompanied by changes in the structure of the eye (Mader et al., 2011; 2016). The root cause for the decrease is under investigation; however, studies suggest that the one-carbon metabolic pathway and the fluid shifts to the head that lead to increased intracranial pressure during spaceflight may play significant roles (Alperin et al., 2018; Mader et al., 2013; Mader et al., 2016; Zwart et al., 2012). A retrospective analysis of magnetic resonance imaging (MRIs) of ISS astronauts showed an upward brain shift with tissue crowding at the upper part of the brain, which caused elevated intracranial pressure and optic nerve swelling. However, the implications of these changes on spaceflight-induced ocular syndrome was not clear because most long-duration crew members had the brain changes but only a few had vision problems (Roberts et al., 2017). Additional studies show that

astronauts exhibited decreases in visual dependence that was maintained throughout 6 months on the space station and persisted for several months after returning to Earth. Such a persistence has implications for crew sensorimotor function (i.e., balance/locomotion) in other gravity environments beyond LEO. Investigators suggest using countermeasures of "visual gravity" (up/down scenes) during long-duration travel to help mitigate these changes in visual dependency (Harris et al., 2017).

After decades of studying bone health in space, investigators found that resistance exercise, coupled with adequate energy intake and vitamin D, can maintain bone in most regions for astronauts on the space station during 4- to 6-month missions in microgravity, providing the first evidence ever that improving nutrition and resistive exercise during spaceflight can mitigate the expected bone mineral density deficits historically seen after long-duration microgravity missions (Smith, Scott M. et al., 2012).

Data collected from saliva samples in astronaut immune studies on the space station indicate that latent Epstein-Barr (infectious mononucleosis) and Varicella zoster (chickenpox/shingles) viruses can become infections under stressful conditions such as spaceflight (Crucian et al., 2008; Mehta et al., 2013; Stowe et al., 2011a; Stowe et al., 2011b). Human T-Lymphocyte cultures flown to the space station showed altered genetic expression of Interleukin-2 and/or its receptor, and, combined with ground studies, suggest a role in the suppressed immunity seen in astronauts (Hughes-Fulford et al., 2015; Chang et al., 2012). Analyses of spleens from mice flown on the space station showed that critical genes involved in T-cell activation of the immune system were suppressed (Martinez et al., 2015). Another study showed that during the transition from a 1-g centrifuge to microgravity on the space station, mammalian macrophage cells immediately decreased their ability to conduct oxidative burst reactions critical in maintaining immune function, but the cells subsequently recovered to their normal capabilities in less than a minute. These results suggest that key cellular functions of multicellular life could successfully adapt to enable long-duration space exploration beyond LEO (Thiel et al., 2017). Researchers at the Veterans Affairs Medical Center in San Francisco discovered a new mechanism of immune regulation by microRNAs in immune cells based on their spaceflight cell culture results (Hughes-Fulford et al., 2015). The previously unknown mechanism is termed "self-limiting induction" and is expected to play a role in global cellular processes including immune response to infection, wound healing and cancer.These studies in healthy astronauts, animals and cellular cultures all provide new insights into how various critical physiological systems respond to microgravity. Results such as these have applications not only to understanding astronaut health as we explore beyond LEO, but also contribute to understanding the health of certain populations on Earth.

Biology and Biomedicine

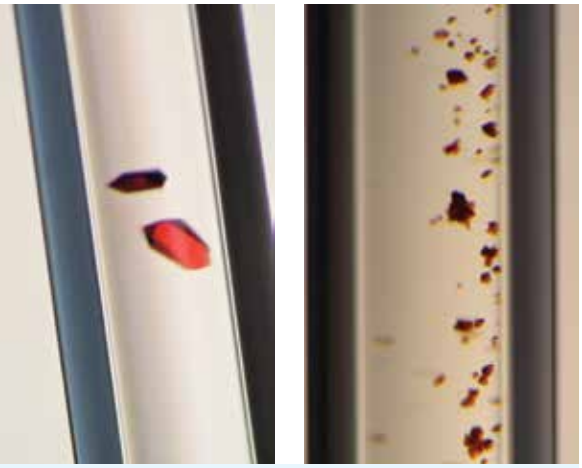
Results from space station biological research have provided insight into complex microgravity responses in experiments ranging from single microorganisms to complex cell cultures, as well as guided successful methods to grow protein crystals in space. The addition of several recent new capabilities have also facilitated an onboard analysis of microbiological and genetic samples for the first time in spaceflight history.

The unique opportunity of long-duration external exposure onboard the space station with the return of samples to Earth has permitted a large range of astrobiology experiments to be performed under actual space conditions (Bryce et al., 2015; Mancinelli et al., 2015; Neuberger et al., 2015; Panitz et al., 2015). Studies such as these have shown that dormant organisms from the three different domains of life—Archea, Bacteria and Eukaryote—are capable of withstanding up to 18 months of exposure to the direct space environment, including solar ultraviolet light, vacuum and radiation. Notably, bacterial spores collected from spacecraft clean rooms were capable of surviving the exposure period, although solar ultraviolet (UV) significantly reduced viability, which has implications on planetary protection and spacecraft sterilization.

New techniques have been successful in the area of protein crystal growth in microgravity. In particular, growing protein crystals in microgravity has led to improved methods to estimate driving force ratios of crystals grown both on the ground and in space,

New capabilities in biological analyses that have been developed and tested on the space station will enable future breakthroughs in molecular and genetics research in space.

as well as the ratio of impurities through the diffusion/capture coefficient of protein. Under microgravity conditions, convection and sedimentation are suppressed; therefore, diffusion areas are maintained, the density around the crystals decreases, the crystals can grow slowly, the capture of impurities and microcrystal decreases, and high-quality protein crystals can be better obtained. These methods contribute to the complex process of drug discovery by revealing disease-related protein structure, and the production of new catalysts for the environmental and energy industries (Sakamoto et al., 2015; Itoh et al., 2016; Kinoshita et al., 2017).



Hemoglobin protein crystal grown on the space station (left) and on Earth (right).

Image credit: JAXA

New capabilities in biological analyses that have been developed and tested on the space station will enable future breakthroughs in molecular and genetics research in space. The first test of a miniaturized flow cytometer in microgravity was performed on the space station to enable real-time onboard biological analyses (Dubeau-Laramée et al., 2014). Flow cytometry focuses fluids (blood or other body fluids) into a controlled stream that enables researchers to quantify specific molecules and monitor physiological and cellular activity. Another instrument sent to the space station proved that it can successfully amplify RNA to allow investigators to conduct molecular biology investigations that provide insight into transient changes in gene expression seen only during microgravity exposure (Parra et al., 2017). In other groundbreaking experiments on the space station, DNA was sequenced for the first time in space using the commercially available MinION DNA Sequencer, and demonstrating the ability for sequencing applications in space, including disease diagnosis and environmental monitoring during spaceflight (Castro-Wallace et al., 2017).

Plant Biology and Bioregenerative Life Support

Results from plant growth on the space station have come from experiments designed for developing bioregenerative food production systems for the space station and for future long-duration exploration missions. In the process, scientists have gained an understanding of some of the basic processes of how plants grow on Earth, and challenged existing scientific theories.

One such experiment made unique observations to attempt to elucidate the underlying mechanisms of circumnutation—a circular movement of growing stem first described by Charles Darwin in 19th century. The unique environment of the space station allowed these experiments to be developed where gravity could be an independent, changeable variable, unlike on Earth. As a result, scientists observed that circumnutation is a result of interplay between the plant's own internal signals, gravity and light—not just gravity alone, as had been theorized (Johnsson et al., 2009; Solheim et al., 2009). Studies of arabidopsis showed that the patterns of root waving and skewing during sprouting are similar on Earth as they are in space, demonstrating for the first time that gravity is not a significant factor for these patterns of root growth. Images also revealed that in the absence of gravity with the presence of directional light, roots grew by skewing to the right, as opposed to growing straight down, away from the light source (Amalfitano et al., 2012). Investigators were able to determine the gravity perception thresholds of plants when grown under various gravitational levels on the centrifuge on the space station (Driss-Ecole et al., 2008); another

The unique environment of the space station allowed these experiments to be developed where gravity could be an independent, changeable variable, unlike on Earth.

research team found that protein expression associated with auxin signaling was decreased while stress response proteins increased (Mazars et al., 2014).

A series of plant experiments performed on the space station showed that the development cycle of plants, their genetic status, morphological and biometric indicators, and basic processes (i.e., photosynthesis, gas exchange, formation of generative organs) do not depend on the spaceflight conditions (Sychev et. al, 2011; Sugimoto et. al, 2014). Higher plants' seeds formed in microgravity were biologically full-featured, and the plants obtained from these seeds did not differ from ordinary "earth" plants. Results also showed that at least four successive generations of higher plants can grow and develop in spaceflight conditions. Developing technology for cultivation of higher plants will offer the possibility of introducing greenhouses as typical human life support systems during exploration-class missions.

Radiation

As astronauts will soon start exploring outside Earth's protective magnetic field, they will be exposed to more space radiation such as cosmic rays or solar particles. The space station provides an excellent platform for testing and developing devices called dosimeters that detect and quantify radiation exposure. A combination of passive and active dosimeters on the space station show how the radiation environment—both total absorbed dose and radiation spectrum—inside the ISS Columbus module changes through the course of the solar cycle, as well as solar events and with alterations in the ISS attitude (Berger et al., 2016). Furthermore, the effects of spacecraft attitude, vehicle docking and local shielding effects on the radiation environment have been observed. This helps in understanding how the radiation environment is affected both by the space environment and by the spacecraft, which is valuable information for the ISS as well as future space exploration missions. Neutron "bubble detector" dosimeters have characterized neutron doses and energy within the ISS over several years. Results showed that despite large differences in solar activities, the neutron environment was fairly constant in ISS modules (Smith et al., 2012; Smith et al., 2015). The data will also support the development of effective protective measures for deep space missions. Results of studies that preceded the ISS quantified radiation exposure to keep astronauts safe while outside the ISS, and found that they received more radiation to the skin, eyes and blood-forming organs than when inside the spacecraft's protective shielding (Thomson, 1999). Another investigation on the space station revealed a substantial lack of uniformity in the depth-dose and surface-dose distributions for spherical "phantom" that simulated an astronaut's body, thus giving an indication of impacts on an actual astronaut's body. The effectiveness of the radiation protection properties of materials containing hydrogen to reduce the doses of charged particles and neutrons was demonstrated while using additional protection in crew quarters. The radiation exposure rate in ISS compartments was assessed for the period of active sun near the maximum of the solar activity in the final stage of its growth (Ambrožová, et al., 2017; Khulapko et. al, 2015; Khulapko et. al, 2014; Khulapko 2016).

The space station provides an excellent platform for testing and developing devices called dosimeters that detect and quantify radiation exposure.

Several attempts to study radiation used living organisms as "biological dosimeters," which revealed genetic mutations within the nematode C. elegans, and contributed to understanding how DNA is affected by space radiation exposure (Zhao et al., 2006; Jamal et al., 2010). Radiation damage is one of the major risks of deep space missions; therefore, data collected on the space station and technologies developed by the international community will play a major role in ensuring the safety of space exploration.

Kevlar fabric material studied on the space station had comparable shielding properties with polyethylene material, which is a traditionally favored radiation shielding material. These results suggest that the impact resistance and flexibility make Kevlar an optimal candidate as a performing element in an integrated shielding approach (Narici et al., 2017).

Materials, Fluids and Combustion

Much of our understanding of physics is based on the inclusion of gravity in fundamental equations. Using a laboratory environment found nowhere else, the ISS provides the only place to study long-term physical effects in the absence of gravity—without the complications of gravity-related processes such as convection and sedimentation. This unique microgravity

Results from space station fluids investigations have allowed investigators to compile a video database of capillary and fluid flows in microgravity.

environment allows different physical properties to dominate systems, and these have been harnessed for a wide variety of investigations in the physical sciences.

Invention of modern materials for different applications is based on complex fundamental studies. Results of materials tested in the unique electromagnetic levitation furnace on the space station have provided data on a wide class of materials such as magnetic, constructive and amorphous alloys that can be used in many practical applications, including coatings with reduced friction coefficient, high corrosion resistance, strength and wear capacity (Krivilyov et al., 2012; Krivilyov and Fransaer, 2012). Investigators on the space station discovered that when melted metals are cooled down in extremely low temperatures and kept away from surfaces, such as inside the electromagnetic levitator, the dendrites of crystals grow very fast. In addition, a higher concentration of the element in the metal (i.e., aluminum) leads to different dendrite growth characteristics. These results suggest that measurements in microgravity are important in understanding how solidification of metals take place (Fecht et al., 2017). In studies of crystallization of metallic alloys, different growth patterns and evolution of microstructures have helped us to better understand the physical principles that govern solidification. These structures play a critical role in the physical properties and behavior of metallic products, and data from ISS solidification of metal alloys have contributed to models that better predict position of columnar-to-equiaxed transition of metal alloys during the solidification process (Zimmerman et al., 2017).

In ISS studies of colloids, where molecules in fluids and gases constantly move and collide, effects of temperature change on such movement (called the Soret effect) have been measured in the absence of gravity, and thus convection. One particular investigation went to space to measure mixtures of tetrahydronapthtalene (THN), isobutylbenzene (IBB) and n-dodecane (nC12). Researchers measured the separation of these chemicals, and calculated the numbers for the Soret effect for these chemicals. Because the Soret effect occurs in underground oil reservoirs on Earth, the results will help us better understand the behaviors of similar components in these reservoirs (Mialdun et al., 2018).

In recent combustion studies on the space station, cool flames were observed unexpectedly following the radiative extinction of burning fuel droplets. This result was not predicted by computational models (based on high-temperature chemistry) nor expected, and has opened up new areas of combustion research in space. Results such as these can lead to a better understanding of both low and intermediate temperature fuel chemistry and effects on droplet combustion, with implications for spray combustion and fire safety (Nayagam et al., 2015). Studies of burning solid materials show that when the opposed flow velocity is increased, the flame spread rate first increases, and then decreases. This was predicted theoretically but had never before been observed experimentally. Data such as these suggest that microgravity could pose a higher fire risk and a more difficult fire suppression, which would have significant implications for spacecraft fire safety (Link et al., 2018).

Controlling the flow of fluids is a challenge in microgravity, which hampers the design of systems such as liquid propellants, thermal control and waste-water management. However, capillary forces, which draw fluids up a narrow tube, continue

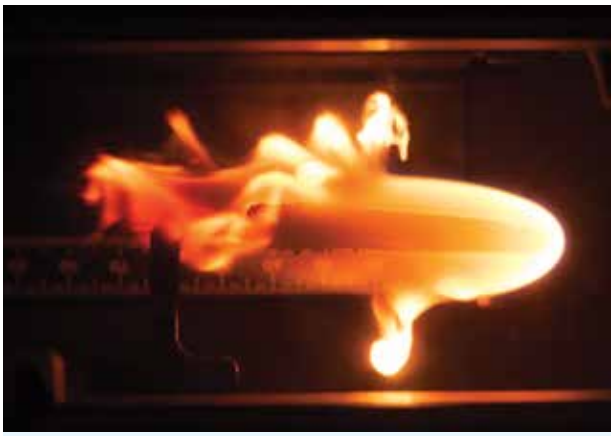


Image taken during a BASS-II (Burning and Suppression of Solids - II) experiment flame test.

Image credit: NASA

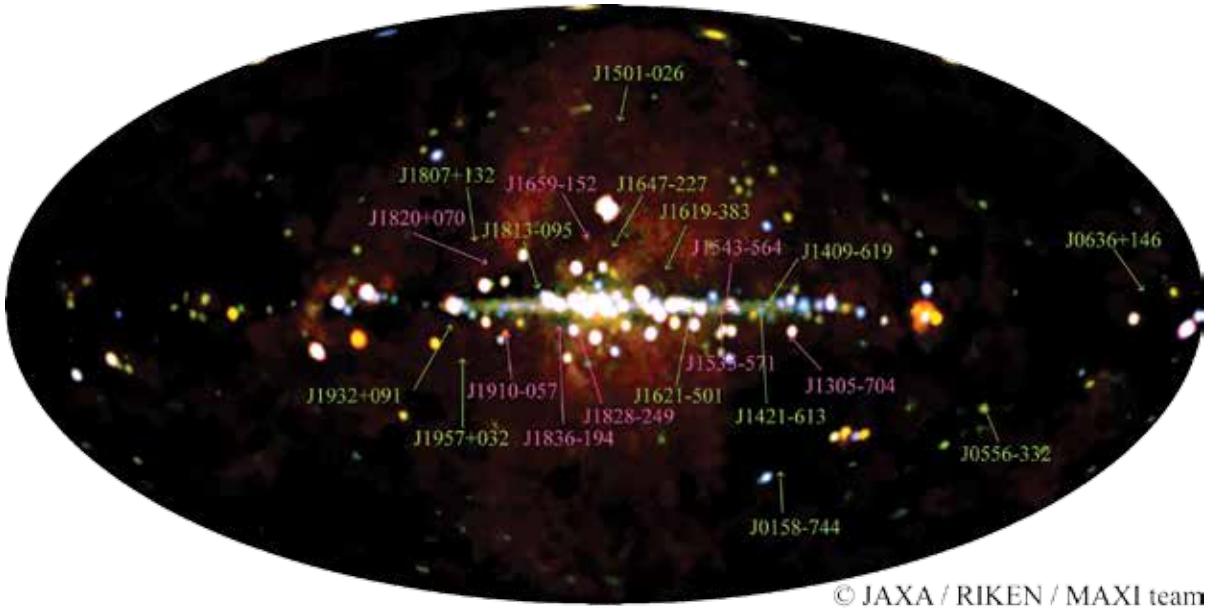
to act in microgravity and can control fluid orientation on spacecraft. Results from space station fluids investigations have allowed investigators to compile a video database of capillary and fluid flows in microgravity. This database has contributed to the use of better computer models for designing microgravity fluid systems such as fluid transfer systems on future spacecraft (Jenson et al., 2010).

Elucidation of Space and Observations of Earth

Even with the many satellites now orbiting in space, the space station provides the required power and data exchange for the powerful instruments that study our universe. Results from all-sky x-ray imaging from the space station has yielded the discovery of eight new black-hole candidates and contributes to observation of transient events in space such as binary X-ray pulsars, stellar flare, active galactic nucleus, tidal disruption of a star by a massive black hole, and hypernova remnant (Burrows et al., 2011; Kimura et. al.,2013; Kimura et al., 2016; Maselli et al., 2014).

Additionally, an analysis of results collected over the first 5 years of operation from the space station has been published in an effort to advance knowledge of the origin of the universe through a search for antimatter, dark matter and measurements of cosmic rays. These results provide information about the positron spectrum and positron fraction, the antiproton/proton ratio, the behavior of the fluxes of electrons, positrons, protons, helium and other nuclei, which in turn provide precise and unexpected information on the production, acceleration and propagation of cosmic rays (Aguiliar-Benitez et al., 2016). Solar irradiance is currently being measured from the space station to contribute to an understanding of our sun's behaviors, and provides coverage of 96% of the total solar spectrum with high accuracy (Bolsée et al., 2017).

Because ISS imagery provides some spectral information as well as street-level resolution, nighttime imagery brings "cultural footprints" to light and are of greater use in epidemiological studies.



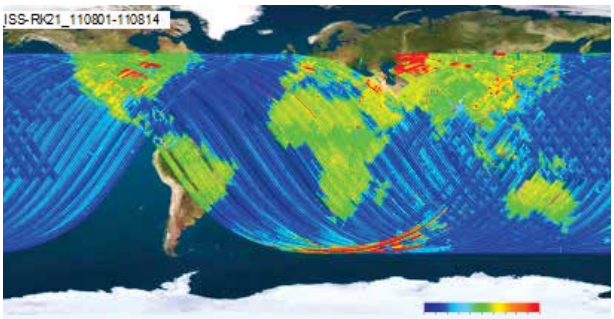
All-sky image with the X-ray camera of MAXI (Monitor of All-sky X-ray Image). The eight black-hole candidates and more than 10 novae discovered with MAXI are shown with the names.

Image credit: JAXA/RIKEN/MAXI team

The presence of the space station in LEO provides a unique vantage point for collecting Earth and space science data. From an average altitude of about 400 km, details in such features as glaciers, agricultural fields, cities and coral reefs taken from the ISS can be layered with other sources of data, such as orbiting satellites, to compile the most comprehensive information available. From Expedition 1 through the present, ISS crew members have taken more than one million images of Earth—almost half of the total number of images taken from orbit by astronauts since the first Mercury missions. Scientists and the public around the world have access to Crew Earth Observations (CEO) images captured by astronauts on the space station through the Gateway to Astronaut Photography of Earth Web site (**http://eol.jsc.nasa.gov**). Scientific analyses using CEO data have been published in scientific journals in a wide variety of disciplines. Images of the Earth at night are an exceptional source of human geographical data because artificial light highlights human activity. Because ISS imagery provides some spectral information as well as street-level resolution, nighttime imagery brings "cultural footprints" to light and are of greater use in epidemiological studies. CEO images are archived in a web-based database and are available to scientists worldwide.

Hyperspectral data from the space station has helped to inform algorithm development for gross ecosystem production (GEP), which is a easurement of energy flow in an ecosystem. GEP data enable scientists to model how changes in CO_2 levels in the atmosphere will impact future agricultural production and to predict ecosystem stability. Researchers from the University of Maryland, Baltimore used remote sensing data from the ISS to develop an algorithm that relates spectrometer imaging data to CO_2 uptake in an ecosystem, and demonstrated that imagery from the space station can be used to map spatial patterns and improve understanding of ecosystem and agricultural productivity. Productivity data enable scientists to model how changes in CO_2 levels in the atmosphere will impact future agricultural production, and to predict ecosystem stability as it relates to agricultural crops, rangelands and forests (Huemmrich et al., 2017).

Microwave radiometry results from the space station provided methods for remote sensing of the Earth in the prospective decimeter range of electromagnetic waves in order to determine changes in soil moisture, vegetation cover parameters, and sea surface salinity. This innovative eight-beam microwave radiometer of the decimeter range allows for the development of new methods for remote sensing of the Earth to aid in our understanding of ocean physics, climatology and weather forecasting, among others (Smirnov et al., 2012; Akvilonova et al., 2013; Smirnov et al., 2010).



Example of microwave radiometry results.

Image credit: ROSCOSMOS

In Summary

The few highlights and metrics in this section were selected among the 2,135 publications resulting from ISS research and clearly show the outstanding diversity in the science performed in LEO.
So far, the investigations have not only solved several risks of human spaceflight, they have improved our knowledge of the universe and contributed to the development of new technologies or processes that already have applications in our daily lives. Considering the difficulties in performing research in the extreme, isolated and weightless environment of space, results of this research are a tribute to the ingenuity and spirit of collaboration of all the contributing countries. Many examples of scientific breakthrough justify the investment and dedication of the whole scientific community and the support of so many countries in ISS operations and maintenance. With all of these results accomplished since the first investigation on the space station, more innovation, discoveries and surprises are to be expected in the years to come.To follow this evolution, including publication of the ISS Annual Research Highlights each year, visit http://www.nasa.gov/stationresults.

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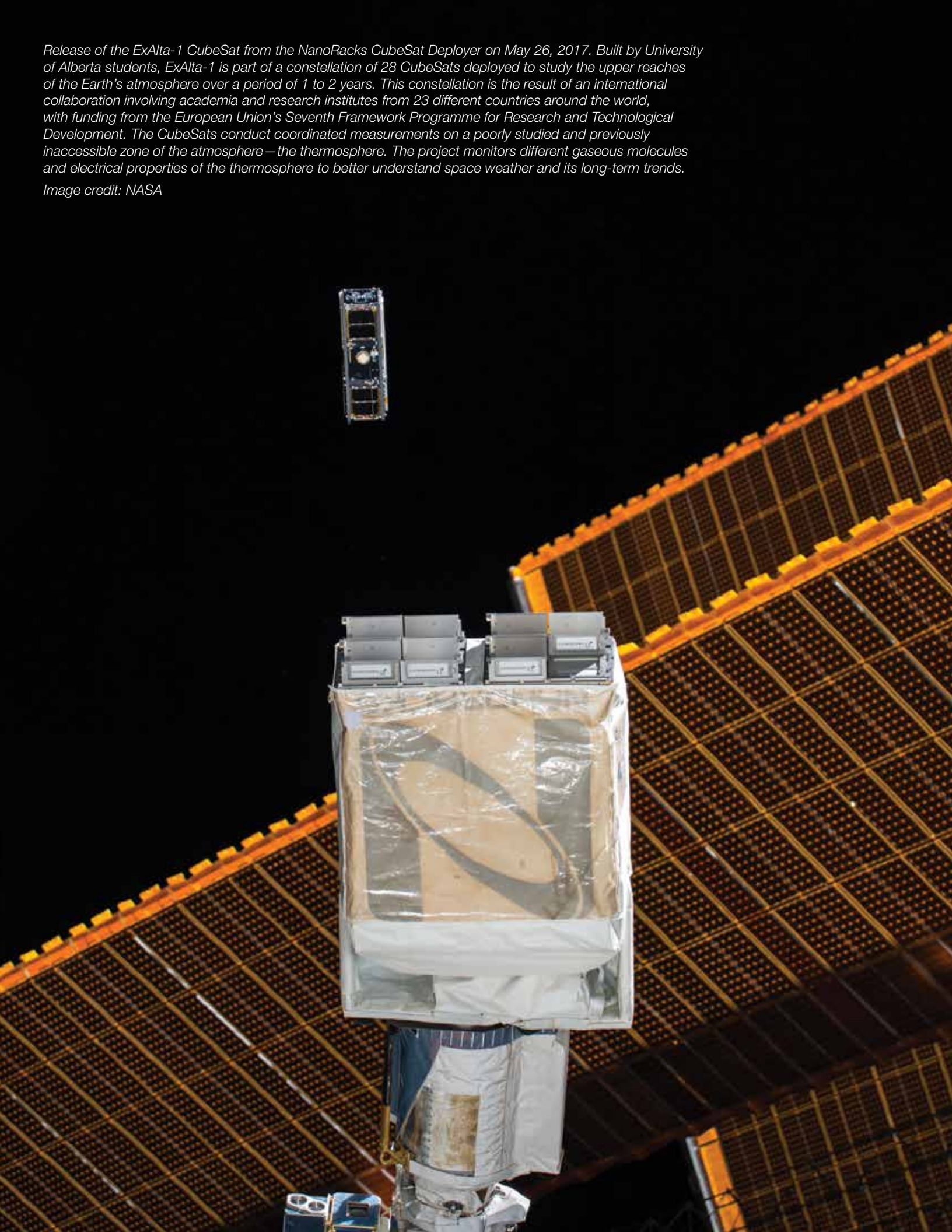
Release of the ExAlta-1 CubeSat from the NanoRacks CubeSat Deployer on May 26, 2017. Built by University of Alberta students, ExAlta-1 is part of a constellation of 28 CubeSats deployed to study the upper reaches of the Earth's atmosphere over a period of 1 to 2 years. This constellation is the result of an international collaboration involving academia and research institutes from 23 different countries around the world, with funding from the European Union's Seventh Framework Programme for Research and Technological Development. The CubeSats conduct coordinated measurements on a poorly studied and previously inaccessible zone of the atmosphere—the thermosphere. The project monitors different gaseous molecules and electrical properties of the thermosphere to better understand space weather and its long-term trends.

Image credit: NASA



Economic Development of Space

The International Space Station (ISS) has proven its value as a platform for advancing the boundaries of understanding in a broad portfolio of research disciplines and technology development areas. However, it also serves as an incubator for new businesses and test bed for new business models. This supports a shift in procurement strategies from a paradigm of government-funded, contractor-provided goods and services to a commercially provided, government-as-one-of many-customers approach.

This interest in promoting a more commercially oriented market in low-Earth orbit (LEO) is driven by several goals. First, it can stimulate entirely new markets not achievable in the past. Second, it creates new stakeholders in spaceflight and represents great economic opportunity. Finally, and perhaps most importantly, it allows cross-pollination of ideas, processes, and best practices as a foundation for economic development.

This section will look at ISS contributions to the growing space economy, from commercial firms spending some of their research and development funds to conduct research on the space station, to commercial service providers selling unique services to users of the ISS, to emerging market developments in the LEO economy.

Growing the Space Economy with Public-Private Partnerships

NASA's interest in using the International Space Station (ISS) as a commercialization platform has been stimulated by a succession of funding and policy bills that have progressively changed the space station's role. In 2004, President George W. Bush announced the "Vision for Space Exploration" that emphasized development of new exploration technologies and human missions to the moon, Mars and deep space. A year later, the NASA Authorization Act of 2005 designated the U.S. segment of the ISS as a National Laboratory to maximize its use by federal agencies and the private sector. The same act also mandated the development of a commercialization plan to support LEO activities. The act required that NASA place at least as much emphasis on encouraging the transfer of NASA technology to the private sector as on encouraging use of private sector technology by NASA. It also directed NASA to develop a plan to maximize the number of contracts awarded to small business concerns.

As a result of these changes in policy focus, the space station—as a laboratory in the vanguard of research in microgravity—increasingly relies on a new and growing number of commercial service providers. Rather than follow the traditional approach of government-funded, contractor-provided hardware or capability, commercial firms develop capabilities that are offered to government as one of many potential users of the ISS as a research platform. The space station gains important new (or updated) capability, while the service provider gains a new market in which to offer its services. From commercial resupply contracts to contractor-provided research facilities, ISS procurement policy changes are enabling a diverse and growing marketplace with new commercial, governmental and academic entities participating in ever-greater numbers.

Enabling Commercial Launch Providers

Although the commercial space launch market encompasses less than 2% of the growing space economy, it has become a high-visibility herald of the growing space economy in the eyes of the global public. Launch capabilities at both the small and large ends of the spectrum have expanded significantly, while reusability of boosters and vehicles is becoming a common occurrence.

The commercial launch market has benefited from changes in contracting mechanisms intended to promote affordable, reliable access to space, with the ISS as just one of many customers. In 2006, NASA initiated the Commercial Orbital Transportation Services (COTS) program and, in 2008, the Commercial Resupply Services (CRS) program. These programs were designed as a demonstration of a public-private partnership model using a fixed-price, pay-for-performance structure.

The SpaceX Dragon 15 cargo craft capture by the ISS Canadarm2 on July 2, 2018.

Image credit: NASA

This reduction in cost-to-orbit opens the door for more participation in the space marketplace, thereby increasing the likelihood for space tourism, space manufacturing and other new services to make a realistic business case for sustained profitability.

Enabling commercial cargo and payload launch services development through a public-private procurement model has proved to be beneficial, with both companies—Orbital Sciences, now Northrop Grumman Innovation Systems (NGIS), and SpaceX—financing the majority of their development costs. During the COTS partnership, NASA contributed $396 million toward the development of the SpaceX commercial cargo transportation systems (i.e., Dragon spacecraft and Falcon rocket), while SpaceX estimates contributing approximately $450 million. Likewise, NASA contributed $288 million toward the development of NGIS (then Orbital Sciences) systems (i.e., Cygnus spacecraft and Antares rocket), while company contributions were estimated to be about $500 million.

The COTS effort proved to be cost effective for NASA when compared to traditional development approaches. All told, NASA invested approximately $700 million while its commercial partners invested approximately $1 billion, meaning the private sector outspent the public sector in developing new space launch capabilities. NASA compared the SpaceX Falcon 9 launch vehicle development costs using the estimated costs of a traditional cost-reimbursement contract versus the COTS milestone-based effort. The NASA models predicted that cost would approach $4 billion.

Increased competition has benefited all customers of commercial launch services. The published commercial launch cost to lift a pound of cargo to low-Earth orbit (LEO) has fallen significantly from early 2000's levels of $8,000 to $10,000 per pound. As of July 2018, SpaceX advertises the standard cost for its Falcon 9 launch services at $62 million, with a maximum payload capability of 22,800 kilograms (50,265 pounds) to LEO. Using these figures, the Falcon 9 cost-per-pound to LEO is approximately $1,200. The Falcon Heavy, at $90 million and 63,802 kilograms (140,660 pounds), would cost under $700 per pound to LEO. This reduction in cost-to-orbit opens the door for more participation in the space marketplace, thereby increasing the likelihood for space tourism, space manufacturing and other new services to make a realistic business case for sustained profitability. (**www.spacex.com/about/capabilities**)

While benefits have accrued to both the government (e.g., NASA's reduced costs in the development of new launch systems) and other customers taking advantage of lower launch costs, both companies involved in ISS resupply have benefitted as well. SpaceX is reportedly the fourth most valuable privately held technology company in the United States, growing from a $100 million investment in 2002, to a valuation of more than $27 billion in 2018. Orbital Sciences Corporation grew in annual revenue from $765 million in 2006 to $1.37 billion in 2013—prior to merging with Alliant Techsystems to form Orbital ATK in 2015. Northrop Grumman purchased Orbital ATK in 2018 for $7.8 billion and rebranded as Northrop Grumman Innovation Systems.

The initiation of new contract vehicles and policies in 2006 and 2008 to support the ISS had the effect of creating a market with predictable and attractive characteristics. Advances in the commercial sector's ability to provide launch services to LEO have included increased capabilities for both large and small payloads, and an increasing number of options in launch providers. Both companies involved directly in providing launch services for ISS resupply missions as of 2018 have gained significant market share. With the ISS as just one of many customers, the U.S. share of the commercial launch market has grown from 9% in 2006 to 64% in 2017. Without ISS procurement policy innovation, the space-access sector may not have matured as quickly as it has.

Northrop Grumman's Cygnus space freighter poised for release from the Canadarm2 robotic arm back into Earth orbit, ending a 52-day cargo mission at the ISS on July 15, 2018.

Image credit: NASA

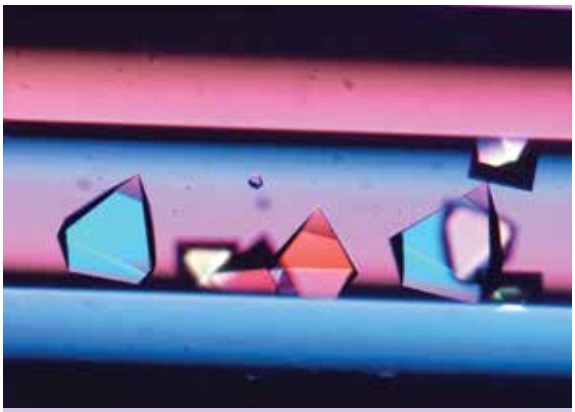
Finding the Keys in Space to Treat Diseases on Earth

A protein that causes disease and a medicine that suppresses it operate much like a keyhole and a key. Determining the shape of the keyhole by examining the protein structure can help create a key to fit it—i.e., an effective medicine with few side effects. Scientists are growing protein crystals on the ISS to design keys to fit keyholes for various medical conditions on Earth.

The High-Quality Protein Crystal Growth (PCG) experiment on the Japanese Experiment Module Kibo is one example. It expands a partnership between PeptiDream Inc, a Tokyo-based biopharmaceutical company, and the Japan Aerospace Exploration Agency (JAXA) to increase by sixfold the experimental protein samples, or keys, investigated.

The partners previously crystallized a nonstandard cyclic peptide drug candidate to target the human epidermal growth factor receptor 2 (HER2). About 1 out of every 5 people with breast cancer makes an excess of HER2 protein, which promotes the growth of cancer cells. Unlike conventional peptide-based drugs, nonstandard peptides have unlimited potential as novel medicines due to their structural stability and longer duration in the human body. The space-grown crystals had substantially higher resolution than those attained on the ground. Results clearly showed the potential drug bound to the receptor via an unprecedented binding mode. These findings are useful to PeptiDream in furthering the development of the drug.

JAXA's previous PCG experiments were conducted at 20°C (68°F) through a collaboration with the State Space Corporation ROSCOSMOS (ROSCOSMOS). When new developments with the private Orbital ATK Dragon cargo spacecraft made it possible for users to choose crystallization temperatures, JAXA launched the 4°C (39°F) PCG experiment.



Protein crystals formed in microgravity in the ISS Kibo module.

Image credit: JAXA

Scientists are growing protein crystals on the ISS to design keys to fit keyholes for various medical conditions on Earth.

"Crystallization at 4 degrees C allows crystallization of candidate drugs in high demand, such as unstable hydrosoluble proteins and membrane proteins," said JAXA's Masaki Shirakawa. "At 20 degrees C, some proteins just aggregate, and do not crystallize. Conducting experiments under 4 degrees C opens the door to space experiments involving unstable proteins."

Early analysis indicates the 4°C (39°F) PCG experiment resulted in high-quality crystals of the protein and the drug candidate complex, thereby accelerating development of the potential drug.

The agreement between PeptiDream and JAXA leverages each partner's strengths—PeptiDream's as a leading drug discovery company, and JAXA's expertise in identifying and optimizing crystallization conditions and the technical ability to carry out space experiments. PeptiDream has established technology that facilitates quick, inexpensive, large-scale production of a wide variety of nonstandard peptides.

"At any stage of the drug discovery process, a high-resolution structure always significantly accelerates this process and having a 3-D structure is truly invaluable," said Patrick Reid, President and CEO of PeptiDream.

"The crystal structure determined from the crystals attained from the JAXA-PCG experiment will significantly accelerate the optimization of these candidates toward clinical candidates," said Executive Vice President Keiichi Masuya.

Kibo and the space station play a key role in allowing PeptiDream and JAXA to obtain structural information on target proteins and their drug candidates swiftly and efficiently, thus aiming to produce new and better drugs for Japan and the world.

Managing the International Space Station National Lab

The 2005 NASA Authorization Act designated the U.S segment of the ISS as a national laboratory and the 2010 Authorization Act directed NASA to develop a plan to "increase the utilization of the ISS by other Federal entities and the private sector…" In 2011, NASA partnered with an independent organization— with the Center for the Advancement of Science in Space (CASIS)—to run the ISS National Laboratory. The focus of the ISS National Laboratory is on advancing U.S. leadership in commercial space and positively impacting American taxpayers by building demand and facilitating investment in activities onboard the ISS.

The ISS National Laboratory is able to utilize 50% of the resources that NASA has rights to for commercial and private research. Thus, factors considered in filling out the portfolio of activities supported include: supporting research and technology development (R&D) across multiple sectors and disciplines; encouraging nontraditional space research participants; and optimizing the potential impacts of R&D activities. In determining the potential benefits, factors such as the estimated addressable market for potential products or services based on the R&D activities are considered as part of the selection process.

The ISS National Laboratory has been successful in attracting Fortune 100 companies such as Proctor & Gamble, Eli Lilly and Honeywell International to use the ISS platform for R&D in fields important to their competitive differentiation. Between 2012 and 2017, the ISS National Laboratory selected 190 investigations

> The focus of ISS National Laboratory is on advancing U.S. leadership in commercial space and positively impacting American taxpayers by building demand and facilitating investment in activities onboard the ISS.

to be carried out onboard the ISS; of these, approximately 56% were commercially sponsored, 42% were academic/nonprofit-sponsored, and only 2% were government-sponsored. In 2017 alone, 45 new projects were selected from more than 100 proposals. Of those selected, 70% represented "new-to-space" customers. According to their 2017 Annual Report, the overall portfolio of ISS National Laboratory activities has an addressable potential market of more than $110 billion.

The goals of commercially sponsored research onboard the ISS are many and varied. For example, Indiana-based Delta Faucet is set to begin a series of research investigations in the fall of 2018. Delta Faucet is developing shower heads that use a special "oscillating chip" to break up the water into bigger droplets and fling it out faster, thereby creating the feeling of more

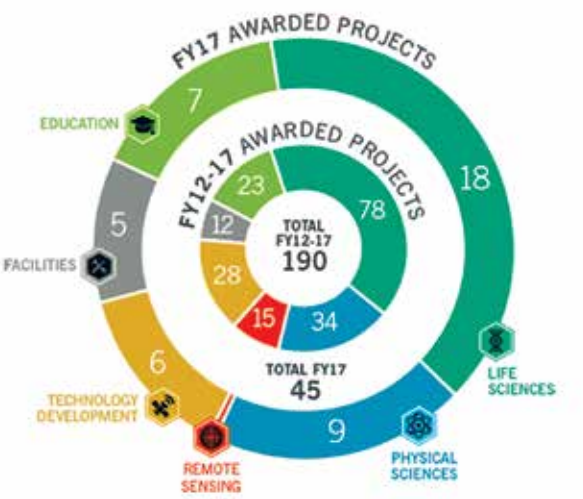


Image credit: ISS U.S. National Laboratory

water while actually using less. Delta Faucet will look to better understand how water flows through the chip in the microgravity environment of the space station, where water forms into floating blobs rather than cascading to the ground. This may help the company make shower heads that use water even more efficiently.

In another example, Goodyear Tire is beginning (as of 2018) a series of investigations onboard the space station to study how silica compounds form in the microgravity environment of space. Silica is an important ingredient in passenger tires and serves to reduce the "resistance" generated as a tire rolls along the road. In typical automobiles, 5% to 15% of the fuel consumption is used to counter this rolling resistance. Therefore, a reduction would result in greater overall automotive fuel efficiency. Silica can form into a variety of different structures even here on Earth. Goodyear wants to find out if new versions of silica, which may be able to offer even better rolling resistance, can be formed in microgravity.

Since 2011, the ISS U.S. National Laboratory has successfully built the foundations of a diverse and potentially impactful portfolio of commercial research. As the 20th anniversary of permanent crewed presence in LEO approaches in 2020, all indications are that the R&D activities within that portfolio will continue to grow and diversify.

Piloting a New Procurement Paradigm

Developing and maintaining water production on the ISS is vital, yet it has presented many challenges as well as new opportunities in the way capabilities are procured. Through 2010, the space station's life support machinery produced breathable air by splitting oxygen from water by using a process known as electrolysis.

The space station is a known test bed for exploration; however, procurement of the Sabatier system demonstrated that the space station can also be a launch pad for procurement options and public-private partnerships.

At the time, NASA did not have the funding to internally produce a system that recycled consumables into water; therefore, it began to consider alternatives such as the Nobel Prize-winning Sabatier process.

The Sabatier process is a well-established water production technology used for many years on Earth. NASA determined an enhanced Sabatier system could reduce water resupply requirements by thousands of pounds of water per year and close the loop in the oxygen and water regeneration cycle. However, the unique space-based Sabatier hardware for the space station was not only a new way of creating water for the crew members, it was also a pathfinder for new procurement contracts.

In the $65 million contract that NASA established with private contractor UTC Hamilton Sundstrand Space, Land & Sea, UTC would engineer the Sabatier system with the stipulation that 100% of NASA's investment would be refunded if the system did not perform upon in-orbit activation. Throughout the development time frame, NASA provided UTC with milestone payments to meet UTC's need for development cash flow. Importantly, the agreement also removed more than 70% of NASA's standard requirements, and verification of the remaining requirements was left as flexible as possible.

The result was that a 249-kilogram (550-pound) stainless steel cube the size of a small refrigerator arrived via Space Shuttle Discovery on April 7, 2010, and was operational by October of that year. The system performed for more than 6 years in

NASA astronaut Douglas H. Wheelock, Expedition 25 commander, is photographed with the Sabatier Assembly—just prior to installation into Oxygen Generator System rack.

Image credit: NASA

orbit, and produced more than 1,080 liters (1,043 kilograms [2,300 pounds]) of clean, safe water for crew members. This represented significant and immediate cost savings in the operation of the space station, and provided a way to produce water rather than transport it all from Earth, thereby increasing the goal of self-sufficiency and broadening the path for extended human survival in LEO and beyond.

The space station is a known test bed for exploration; however, procurement of the Sabatier system demonstrated that the space station can also be a launch pad for procurement options and public-private partnerships. Commercial providers believed that they could deliver a Sabatier system at a significantly reduced price if the government would allow them to do so. This experience served as a pathfinder for innovative contracting on the space station, including the emergence of new partnerships in commercial facilities.

A New Approach to Radiation Hardening Computers

In August 2017, the SpaceX CRS-12 resupply mission brought a supercomputer to the ISS. This supercomputer, dubbed the Spaceborne computer, was part of a year-long experiment to run a high-performance commercial off-the-shelf computer system in space, with the goal of having the system operate seamlessly in the harsh conditions of space for 1 year—roughly the amount of time it will take to travel to Mars.

Computing capabilities in space are greatly reduced compared to state-of-the-art supercomputers available on the ground, which creates a challenge when transmitting data to and from space. Although relying on ground-based computers works for space exploration on the moon or in LEO, when astronauts can be in near real-time communication with mission control back on Earth, this will not do once they begin to travel farther into the solar system, where they will experience larger communication delays. For example, it can take 20 minutes for a transmission to reach Earth from Mars.

The Spaceborne computer is a commercially available supercomputer designed and produced by Hewlett Packard Enterprises (HPE). It includes HPE Apollo 40-class systems with a high-speed HPC interconnect running an open-source Linux operating system. According to HPE, the Spaceborne computer contains compute nodes of the same class as NASA's premier supercomputer, Pleiades. As of November 2017, Pleiades was ranked one of the 20 fastest high performance computers in the world according to the High Performance Conjugate Gradients (HPCG) Benchmark project and the TOP500 List.

Perhaps even more important than its computational speed is the innovative method HPE chose to protect that speed from the negative effects of space. HPE created system software to mitigate negative impacts of radiation on computer reliability. In the past, computers have been physically "hardened" to protect against radiation coming from such sources as solar flares and cosmic radiation subatomic particles. Physical hardening takes time and money, and adds weight; therefore, this innovative software approach could have a huge impact on the computing capabilities of future space exploration missions.

During its demonstration mission, the Spaceborne computer successfully performed more than 1 trillion calculations (or one teraflops) per second for 207 days without requiring reset. This is achievable due to HPE's software-hardening process, which protects the hardware from extreme temperatures, radiation and other environmental factors.

Radiation-resistant computers improve the reliability of computational resources in space; however, radiation events (e.g., solar flares) can also pose risks to computing resources on Earth. As computing devices are increasingly used in an expanding range of outdoor applications such as cellular towers and traffic monitoring systems, radiation can have a number of unanticipated effects on complex computer systems. The Spaceborne investigation enables dynamic software solutions, and helps identify critical failure points in electronic systems as well as potential software patches that can prevent them.

The Spaceborne computer demonstration is another example of the public-private partnership model. Sponsored by the ISS National Laboratory, HPE independently designed and produced the supercomputer without NASA funding while still meeting NASA's requirements for protecting critical hardware from extreme environmental conditions. As of April 2018, Spaceborne computer was still demonstrating teraflop performance rates while showing only a 0.03% difference to the ground computers running in parallel. The Spaceborne team has also demonstrated and publicized their results in many industry conferences, widely communicating ISS capabilities and achievements to audiences typically not engaged in ISS research.

Commercial Research, Facilities and Service Providers

The International Space Station (ISS) is not a traditional asset where concepts such as return on investment (ROI), payback period or risk-adjusted return are easily applied. Instead, the ISS benefits to humanity emerge as catalysts for technological innovations, space utilization and, more recently, commercialization. Research facilities onboard the space station have evolved in recent years from primarily government funded and operated to commercially owned and operated. Since 2012, commercial research facilities have greatly increased the breadth and volume of ISS-supported research.

Commercial Partners Expanding International Space Station Research Capabilities

During the first six crew rotations aboard the space station, 166 research and technology development (R&D) investigations were conducted. During the last six crew rotations (as of May 2018), 416 R&D investigations were supported. Although the amount of crew hours available has increased, the most significant factor driving this increase is the proliferation of commercial research facilities aboard the space station.

NanoRacks LLC was one of the first commercial partners to operate research facilities onboard the ISS. Beginning with the installation of the first NanoRacks Internal Science Platform in 2010, they applied the standardized CubeSat dimensional form factor (10 x 10 x 10 centimeters [~4 x 4 x 4 inches) to provide "plug-and-play" research capabilities aboard the ISS. As of 2018, Nanoracks operates three of these platforms designed for use within the pressurized space station environment. Each is approximately 43 x 23 x 51 centimeters (17 x 9 x 20 inches), weighs approximately 5.5 kilograms (12 pounds), and provides room for up to 16 payloads in the CubeSat form factor.

NanoRacks offers complete in-house capabilities for payload integration, payload design and development, and interfacing with NASA and the ISS international partners. The core payload hardware supported by these platforms are called NanoLabs. Every NanoLab has a circuit board that activates the experiment housed within, turns it off, and can be functioned for other activities. NanoLabs are plugged into the research platforms via a normal Universal Serial Bus (USB) port, thus allowing data and power to flow and can even be developed by third-party vendors. A single NanoLab is 1U (i.e., one unit) in size, but the platforms can also support 2U, or 4U or 2 by 4U sizes, with cost varying by the size of the NanoLab. This plug-and-play system uses a simple, standardized interface that reduces payload integration cost and schedule for nanoscale research in microgravity.

Through the standardization of test hardware and implementation of the CubeLab approach, the cost of conducting research in orbit has been reduced as much as threefold...

As of 2018, NanoRacks has supported more than 300 investigations on the ISS and operates multiple facilities both internally and externally on the space station. Examples of the range of research conducted by customers include the NanoRacks-PCG Therapeutic Discovery investigation, which tested whether microgravity improved the crystallization of two proteins that are important for future treatment of heart disease and cancer. The NanoRacks-Hydrofuge Plant Chamber Experiment aimed to overcome the behavior of water in microgravity, which has caused root rot in plant systems. In addition, dozens of student-designed payloads from the elementary education through graduate student level have been supported.

Through the standardization of test hardware and implementation of the CubeLab approach, the cost of conducting research in orbit has been reduced as much as threefold between 2006 and 2018, and accessibility has greatly increased. In 2006, the cost for conducting educational research projects on the

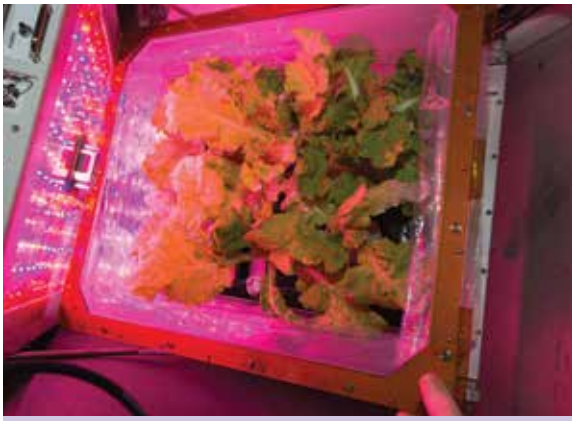
ISS that did not require specialized equipment was typically just under $100,000. As of 2018, NanoRacks advertised charges of $35,000 for a basic NanoLabs CubeLab module. This includes filing the necessary paperwork, manifesting the payload on an ISS resupply vehicle, installing the equipment, and taking care of all government relations for the research, with a standard 30 days of research on an ISS facility.

As of 2018, at least 15 active commercial facilities are operating onboard the ISS, with companies such as BioServe, Made In Space, NanoRacks, Space Tango, TechShot and Teledyne Brown Engineering leading the way toward expansion. Many of these organizations have used their own resources to invest in on-orbit research and development facilities, thereby reducing the risk for the federal sector to develop these facilities and services. In addition, many of these facilities can provide remote control of experiments from the ground, thus freeing up valuable crew time to focus on those tasks and investigations that truly need hands-on attention. These companies find research customers through the ISS research partners, the ISS National Laboratory, and their own business development efforts to enable the R&D for research customers.

For example, the Space Automated Bioproduct Laboratory (SABL) is a commercial facility developed by Bioserve that can support a range of investigations across life sciences, physical sciences and materials sciences. The SABL has interchangeable inserts that allow it to support fundamental and applied research ranging from microorganisms through small organisms, cell and tissue culture, and small plants. An important feature on the SABL is its USB compatibility, which allows support of any future scientific tools with USB connectivity to work with SABL.

The Multiple User System for Earth Sensing Facility (MUSES) is an example of a commercial research facility housed externally on the ISS. Developed in a cooperative agreement between Teledyne Brown Engineering and NASA, MUSES provides many commercial companies the opportunity to conduct their science and research in space. MUSES supports many different kinds of investigations and hardware, providing precision pointing and other accommodations for various kinds of research and science disciplines.

Another example, Veggie, is a low-cost plant growth chamber that uses a flat-panel light bank that includes red, blue and green light-emitting diodes (LEDs) for plant growth and crew observation. Veggie's unique design is collapsible for transport and storage and expandable up to a 0.5 meters (1.5 feet) as plants grow inside. Sierra Nevada Corporation's wholly owned subsidiary, Orbital Technologies Corporation (ORBITEC) in Madison, Wis., developed Veggie through a Small Business Innovative Research (SBIR) Program. NASA and ORBITEC engineers and collaborators at NASA's Kennedy Space Center in Florida worked to get the unit's hardware flight-certified for use on the space station.



Chinese cabbage plants for the Veg-03 experiment growing in the Vegetable Production System (Veggie).

Image credit: NASA

NASA astronaut Peggy Whitson poses with cabbage plants in the Vegetable Production System (Veggie) bellows in the Harmony Node 2. Image was taken during final harvesting operations for the Veg-03 experiment.

Image credit: NASA

As represented by the examples above, proliferation of ISS commercial facilities is ongoing, with processes in place to aggressively target, monitor and manage lab capacity to ensure the space station maximizes the impact it has on economic, social and innovation outcomes. A number of enterprising companies have targeted low-Earth orbit (LEO) and the ISS as integral elements of their business plans going forward.

The ISS has opened the doors to LEO for commercial entities, researchers and scientists. Private industries collaborate with government agencies to provide services and facilities to researchers, taking advantage of the space station's microgravity environment.

Research in a Box*

**Part of this article is reprinted with permission from Upwards Magazine (V2,3),*

New-to-space companies and investors who have never explored space's resources are using the ISS National Lab as a platform for innovation, discovery and commerce. To support this growth, Kentucky-based Space Tango is filling new demand for expanding space-based research and development by paradoxically shrinking labs into something small enough to be held in both hands.

The space available for R&D on the ISS is significantly more constrained than labs on Earth—access to mass, volume, power and crew time are precious. To address this constraint, Space Tango works with researchers to offer the capabilities of a full lab condensed into a 10-centimeter (4-inch) CubeLab Module.

Following in the footsteps of other companies before them, an experiment in one of Space Tango's CubeLabs can be "plugged into" the ISS and either run automatically until it returns to Earth or be manually controlled from the ground. For Space Tango, microgravity is the next frontier in advancing scientific discovery and expanding the universe of R&D in space.

TangoLab-1 arrived on the ISS in August 2016 and is roughly a half-meter by half-meter (58 x 46-centimeter [~23 x 18-inch) platform that houses up to 21 CubeLabs and provides power and communication links for experiments. The TangoLab-2 facility was launched to the ISS in August 2017, adding a few new capabilities and taking the number of experiments Space Tango can accommodate at a time from 21 to 42—dramatically expanding the number of customers that can conduct experiments on the ISS National Lab.

The TangoLabs are permanent fixtures on the ISS, but CubeLabs—and thus experiments—can be swapped out so that experiments can be repeated as is or modified in real time to meet the needs of the investigator. Each 10 x 10 x 10-centimeter (~4 x 4 x 4-inch) CubeLab makes up a unit—known as a U—and can house a single experiment, whether it is from the life sciences, material sciences, or another field of study. Alternatively, an experiment can take up 2U, 4U or even 6U, if needed. CubeLabs also contain the necessary attachments required for experiments, such as LED lights or imaging equipment.

Because many researchers do not have experience in spaceflight R&D, Space Tango works with customers to modify ground-based experiments to meet the demands of the space environment and make R&D objectives technically feasible.

Flight Engineer Mark Vande Hei swaps out a payload card from the TangoLab-1 facility and places it into the TangoLab-2 facility. TangoLab provides a standardized platform and open architecture for experimental modules called CubeLabs. Pictured here are a pair of CubeLabs that are 2U and 1U in size.

Image credit: NASA

Experiments within the CubeLabs are fully automated and designed to require minimal human intervention, which is a plus, as crew time is highly valuable. Real-time or near real-time data can be sent from the CubeLabs to customers on the ground, allowing them to stay up-to-date on their experiment's progress. Additionally, the TangoLabs come with several standard kits, including cell culturing as well as plant and bacterial growth kits. TangoLabs are a general research platform and are not built for any specific use, making them highly customizable.

"You can build a lot of the analytics and environmental controls into each individual CubeLab, which allows us to have a plant growth study next to a bacteria study," explains Twyman Clements, cofounder and CEO of Space Tango. "A lot of the 'smarts' are inside the cube itself."

In February 2017, Space Tango's first customer payloads, including experiments from commercial and educational organizations, were transported to the ISS on SpaceX CRS-10. Because of the successes of these projects, a second facility was launched to the ISS on SpaceX CRS-12 in August 2017, doubling the number of experiments Space Tango can support on a single mission.

Because many researchers do not have experience in spaceflight R&D, Space Tango works with customers to modify ground-based experiments to meet the demands of the space environment and make R&D objectives technically feasible. Space Tango's CubeLabs make experimenting in space more accessible and affordable to customers interested in harnessing the power of space to advance their R&D on Earth.

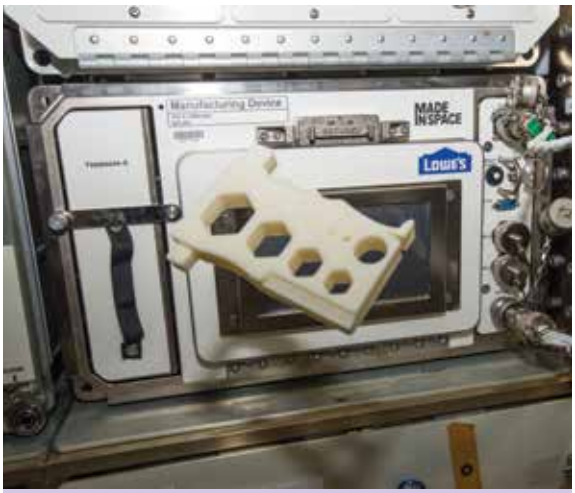
Researchers may be experts in their fields of study, but most are unaccustomed to the different challenges presented by working in microgravity. Procedures as simple as pouring liquids into a beaker must be altered to work on the ISS. Space Tango uses its team's expertise in spaceflight R&D to adjust experiments to microgravity and fit them within the CubeLab.

Made In Space—Building a Better Optical Fiber

In 2014, the ISS Additive Manufacturing Facility (AMF) produced the first three-dimensional (3-D) printed object in space. Traditionally, it can take months or even years, depending on the launch resupply schedule, to get equipment to space. For exploration missions, resupply from Earth may be impossible. Enabled by a series of eight NASA SBIR contracts, commercial facility provider Made In Space, Inc. became the first company to 3-D print in space, thus paving the way to future long-term space expeditions and the possibility of manufacturing tools in orbit.

In 2014, the ISS Additive Manufacturing Facility (AMF) produced the first three-dimensional (3-D) printed object in space.

Made In Space is an American company with more than 45 employees currently operating the 3-D printing (AMF) onboard the space station. In early 2011, Made In Space was a small company with a 3-D Printing Lab housed inside the NASA Ames Research Center. By 2012, the company had conducted multiple suborbital flights on NASA's reduced-gravity aircraft, and received more than $1 million in NASA Phase I & II SBIRs for the development of the AMF. By 2013, NASA announced plans for the "3-D printing in Zero-G" technology demonstration onboard the space station. The demonstration of the Made In Space 3-D printing was a successful first step toward establishing an on-demand machine shop in space—a critical enabling component for deep-space crewed missions and



A printed product floats in front of the AMF on the ISS.

Image credit: NASA

in-space manufacturing. As a result, Made In Space partnered with Lowe's Innovation Labs in 2016 to launch and install the AMF—the second-generation, space-based 3-D printer—on the ISS. To date, this privately owned facility has manufactured more than 100 parts, tools and assemblies for both commercial and government customers.

In 2018, Made In Space secured a NASA SBIR contract for the development of the Vulcan Advanced Hybrid Manufacturing System, which will "address NASA's requirement to produce high-strength, high-precision components on-orbit with comparable quality to commercially-available, terrestrial machined parts." The facility will essentially be a powerful upgrade to the capabilities enabled by the AMF that is currently installed on the space station. Additionally, Made In Space has received a $20 million NASA contract to develop Archinaut, a platform for the additive manufacturing and assembly of large, complex systems in space without astronaut extravehicular activity. The project is a partnership between Made In Space, Northrop Grumman Corporation and Oceaneering Space Systems.

In 2016, plans to begin the commercial manufacturing of high-fidelity optical ZBLAN fibers in space via its Made In Space fiber facility were announced. Theoretically, ZBLAN fibers produced in space develop smoothly and clearly, and with far fewer defects, unlike those produced on Earth. ZBLAN is fluorine combined with metals: zirconium (Zr), barium (Ba), lanthanum La), aluminum (Al) and sodium (Na), hence the name. ZBLAN offers significant advantages over the traditional silica-derived optical fibers used commonly around the world. ZBLAN fibers offer two advantages. First, because they can transmit a broader spectrum, several lasers of different colors could use the same fiber at the same time. Second, they absorb less light (look through the edge of a window pane and you see how quickly light is extinguished); therefore, fewer signal boosters (called repeaters) are needed in long-distance cables.

Fabricating ZBLAN fibers on Earth has proven to be difficult due to the convection processes involved at 1-g, and the formation of bubbles and crystals in the pulled fibers. In 1998, NASA demonstrated that heating ZBLAN fiber to its crystallization temperature in 1-g rapidly produced crystals; however, the same temperatures in low-g conditions did not produce a crystal lattice. The major benefit of ZBLAN fibers over silica fibers, or any fibers, is that a perfect ZBLAN glass should transmit light near the theoretical best allowed by matter. In collaboration with Thorlabs Inc., Made In Space conducted the Optical Fiber Production in Microgravity investigation on the ISS from September 2017-2018 to set the stage for large-scale manufacture of high-quality fiber optics in orbit.

Small Business Makes Big Strides in Commercialization of Low-Earth Orbit

The path to discovery and exploration is paved with determination, innovation and, most of all, big ideas. The ISS is home to many of those ideas and is creating new ways for small businesses, entrepreneurs and researchers to test their science and technology in space every day.

Formed in 2015 in response to the need for a commercial payload that would be available to private companies aboard the space station, Alpha Space is

The Materials ISS Experiment-Flight Facility (MISSE-FF) in the Japanese Experiment Module (JEM) prior to transit through the JEM airlock inner hatch and mounting on the JEM external facility.

Image credit: NASA

The path to discovery and exploration is paved with determination, innovation and, most of all, big ideas.

a woman- and minority-owned small business responsible for developing the Materials International Space Station Experiment Flight Facility (MISSE-FF).

MISSE-FF, a permanent platform affixed to the exterior of the space station, offers private researchers and scientists the ability to tests materials, conduct technology demonstrations, and test items such as circuitry, cameras and computer boards against the harshest of environments: space.

"You no longer have to be a NASA scientist to get your experiment on the space station," said Stephanie Murphy, founder and chairman of Alpha Space. "You can be a private entity, an entrepreneur, a researcher, someone in Academia, and your research can fly and it can fly quickly."

MISSE began in the early 2000s with one-time use, suitcase-style platforms that would open up and expose materials to the space environment. MISSE-FF is robotically serviceable and commanded from the operations center at Alpha Space. This feature gives the platform the serviceability and changeability to allow for continuous science to occur for the next 10 years.

Alpha Space represents only one of the commercial pathways to the space station, with NanoRacks, Space Tango, Made In Space, Techshot, and more also making their way through LEO.

"Every day new commercial companies are coming into the fold of this new economy that's developing," said Murphy. "I think the space station is a great platform to start commercialization, but I anticipate that it will continue to lunar orbit and beyond and support NASA missions, but also run in parallel, a unique commercial industry and economy all its own."

MISSE-FF was launched aboard the SpaceX-14 Commercial Resupply and began service in 2018. It is sponsored by the ISS National Laboratory.

European Space Agency ICE Cubes

Europe's new commercial research facility on the ISS, called ICE Cubes or International Commercial Experiment Cubes service, offers plug-and-play installation for cube-sized experiments in microgravity. For the first time, ICE Cubes users are able to interact with their experiments directly from the ground and

For the first time, ICE Cubes users are able to interact with their experiments directly from the ground and receive experiment data.

View of the MISSE-FF taken by the External High Definition Camera on April, 19 2018. The MISSE-FF platform provides the ability to test materials, coatings, and components or other larger experiments in the harsh environment of space.

Image credit: NASA

The ICE Cubes Facility located in the Columbus European Physiology Module rack is a capable experiment platform that offers flexibility to host many different experiments in the CubeLab form factor. Pictured is the first experiment module hosted in the facility (taken June 5, 2018).

Image credit: NASA

receive experiment data. The ICE Cubes service was enabled by a commercial partnership between Space Applications Services, Belgium, and the European Space Agency (ESA), and is part of the agency's Space Exploration Strategy to ensure access to the microgravity research possibilities in LEO.

ICE Cubes are small, modular containers that slot into a rack drawer about the size of a microwave oven on the Columbus laboratory, and connect to electrical power and monitoring systems. The ICE Cubes service allows experiments to run for more than 4 months in space, and include astronaut time and expert advice as part of the package. If required, experiments and samples can be returned to Earth for analysis.

The first experiments were installed by ESA astronaut Alexander Gerst in July 2018 and include projects supplied by the International Space University. The first experiment is researching methane-producing microorganisms and how they behave in space. These examples highlight the versatility of a simpler, faster and more affordable access to research on the ISS, ensuring any company, entity or educational institution can be a part of microgravity research in space for years to come.

The Commercial Multi-use Variable-g Platform

Delivered to the ISS aboard SpaceX CRS-14, the Techshot-developed Multi-use Variable-g Platform (MVP) is a new commercial test bed for centrifuge-based science aboard the space station. Because gravity determines so much of a live organism's behavior and growth, centrifuge-based experiments have long been a part of biological investigations in space. Although the pull of Earth's gravity makes this type of investigation difficult at home, the space station's microgravity environment makes it the perfect place for fractional gravity experimentation. MVP greatly expands that testing capability for the space station.

MVP vastly expands commercial and research opportunities in LEO. Several investigations are already lined up for the platform, and customers include government, academic and commercially based teams. "This is a permanent, commercially owned research facility that gives researchers the opportunity to study the effects of gravity and partial gravity on living organisms, and, hopefully, by extrapolation to humans," said Rich Boling of Techshot, the company responsible for MVP's design and build.

What makes the facility so special is its size and capability. Containing two carousels that spin quickly to simulate up to two times the force of gravity, the platform is the largest centrifuge in the U.S. segment of the space station and allows investigators more room for, and control over, their research. With room for six experiment modules on each carousel, Techshot can fly up to 12 separate modules on MVP at a time. Each module is equipped with temperature sensors, and the box that houses the carousels and modules can be set to the exact environmental specifications requested for any investigation.

When asked what kinds of investigations the platform could host, Boling said, "It's really whatever investigators could dream up that they want to put inside of these experiment modules. Each one empty is about 800ccs of volume. So whatever a research team wants for that volume, we can make it happen, get it up there, and get it back. For example, we have a tissue chip investigation

Delivered to the ISS aboard SpaceX CRS-14, the Techshot-developed Multi-use Variable-g Platform (MVP) is a new commercial test bed for centrifuge-based science aboard the space station.

Techshot's MVP allows researchers to control and vary the level of gravity for their experiments using centrifuge technology.

Image credit: Techshot

coming up this year for a team at the Massachusetts Institute of Technology."

Said Boling of working with NASA, "The payload that eventually became MVP started out as a Small Business Innovative Research proposal." After 7 years and several phases of development, investment and product improvement, Techshot was able to secure six research campaigns to get MVP started. These campaigns include research from industry and academia, and two additional investigations for NASA in 2019.

Mixing Up Better Products in Microgravity

Consumers want products that last, are easy to use, and perform as promised. To provide these products, companies sometimes take research to a higher level—as in LEO aboard the ISS.

Increasing numbers of companies are taking research to microgravity; however, spaceflight has been part of R&D at Procter & Gamble (P&G) for almost a decade. In partnership with NASA, the ISS National Laboratory, Harvard University, Case Western Research and ZIN Technologies, P&G has conducted a series of investigations in microgravity of how gas and liquid phases form microstructures and how these structures change over time. The studies, collectively known as the Advanced Colloids Experiment (ACE), use blends of colloidal particles as proxies for commercial materials. Colloids—suspensions of microscopic particles in a liquid—are found in products ranging from milk to fabric softener.

The Light Microscopy Module is configured for ACE-T-1 experiment.

Image credit: NASA

Increasing numbers of companies are taking research to microgravity; however, spaceflight has been part of R&D at Procter & Gamble (P&G) for almost a decade.

These products depend on the stability of such mixtures, particularly polydisperse mixtures, or those with particles of different sizes in suspension. Studying how these mixtures move and break down helps product designers and manufacturers create better, longer-lasting products that maintain all their desired features.

"In simplest terms, we are trying to develop ways to formulate together otherwise incompatible ingredients," explained Matthew Lynch, P&G principal scientist. "We do this with the structured fluid approach—creating microstructures in the fluid that keep these ingredients together to ensure the same great performance from first to last use. In products that contain incompatible ingredients, structured fluids keep them from separating—for example, cream on top of milk."

Shampoo, for example, must flow out of the bottle like a liquid when used; however, in transport and on a shelf, the solution needs to behave almost like a solid, with droplets of active materials remaining evenly dispersed. "We need to get the interactions just right to meet both sets of conditions," said Lynch. "Experiments in microgravity allow us to ask basic science questions about how these mixtures behave and will eventually have a tangible effect on consumer products."

The microgravity environment is key because, on Earth, gravity causes heavy particles to sink and lighter ones to float almost immediately. That makes it difficult to understand what is happening and why.

About two-thirds of P&G's biggest brands could benefit. Downy fabric softener alone has sales of about $4 billion a year, so a mere 1% savings in production costs, getting to market faster, or a slightly longer shelf life provides significant return on investment. P&G spends millions of dollars a year on research to address product shelf-life problems.

ACE includes these six investigations:

- Advanced Colloids Experiment-Microscopy-1 (ACE-M-1), on behavior of microscopic particles in liquids, gels and creams, including keeping stabilizers from clumping and sinking—a process known as coarsening.
- ACE-M-2, continued work in phase separation of liquids and gases in microgravity that could benefit a wide range of fluid storage, and transport and processing systems for future spacecraft, as well as provide household product formulations with maximum stability and shelf life.
- ACE-M-3, on design and self-assembly of complex 3-D structures from small particles suspended within a fluid medium.
- Advanced Colloids Experiment-Temperature control-1 (ACE-T-1), on fundamental behaviors of colloids, including self-assembly.
- ACE-T-6, microscopic behavior of colloids in gels and creams, including those with varied particle size.
- ACE-T-7, continued investigation of design and self-assembly of complex 3-D colloid structures.

This basic scientific knowledge about how varied mixtures and particles behave allows manufacturers to predict characteristics such as shelf life for a wide variety of commercial products. However, the research has many other potential benefits. More-concentrated products use less packaging, resist collapse and remain consistent, which reduces production and transportation costs. Better formulas can improve liquid pharmaceuticals. Longer shelf life means some perishable items can be stored long-term for disaster preparedness.

In addition, future space exploration may employ self-assembly and self-replication to make materials and devices that can repair themselves. Ultimately, structures based on colloids may produce new devices for chemical energy, communication and photonics.

P&G has already seen direct results from its research in microgravity, with three patents published that, within a few years, could result in new or improved commercial products.

Particles ACE a Test in Stability

The Advanced Colloids ExperimentACE (ACE) suite of investigations studied the microscopic behavior of polymethyl methacrylate (PMMA) particles and their ability to remain physically and chemically stable for longer periods of time on Eearth and in the microgravity environment. These findings show that PMMA particles open doors for accomplishing never- before-performed experiments.

Combating Muscular Atrophy with Implantable Devices

Extended spaceflight takes a toll on many systems within the human body, including the musculoskeletal system. An investigation aboard the ISS will examine a drug compound and a drug delivery system aimed at preventing, slowing or even reversing muscular breakdown, both in space and on Earth.

Rodent Research-6 (RR-6), a twofold investigation, will study the effectiveness of both the drug compound and the nano-channel drug delivery implant for their use in the treatment of muscle loss in future spaceflight, and in the treatment of patients with muscle-wasting diseases or conditions on Earth.

The drug compound will be administered through a device implanted beneath the skin, allowing for a constant, steady delivery of the drug.

“The unique aspect of the mission is the nano-channel delivery system is implanted under the skin and provides constant drug delivery in the body, which prevents the need for injections or taking pills,” said Yasaman Shirazi, the project’s mission scientist at NASA Ames Research Center, “and if you want to

An investigation aboard the ISS will examine a drug compound and a drug delivery system aimed at preventing, slowing or even reversing muscular breakdown, both in space and on Earth.

look at it long-term, it could be a customized device for long-term curing of a disease."

Using channels just 2 to 3 nanometers in size and a device roughly the size of a grain of rice allows for a controlled delivery using simple diffusion, rather than requiring a pumping mechanism.

"We realized if we use channels comparable in size to the drug molecule of interest, we can achieve a very steady, controlled delivery of drug outside of an implanted reservoir for a period of time ranging up to months and years without any sort of pumping mechanism onboard our implants," said Alessandro Grattoni, the project's primary investigator at Houston Methodist Research Institute.

Once the drug reservoir is depleted, the implant can be refilled rather than replaced. Without being removed, the implant reservoir can be reloaded using two needles through the skin. Although this investigation will not be using this capability of the device due to the short time frame of the study, Grattoni said it would be an important feature for long-term treatment or prevention of muscle wasting, as well as other chronic conditions.

Scientists gain insight into the workings of the human body by studying mice, given their genetic similarity to humans. The rodents' faster development and shorter life span reveal effects of microgravity on an expedited timescale.

"Animal models are great translational models because they provide us the ability to collect data and samples we are typically not able to collect in human subjects," said Shirazi.

"Doing all of these studies in microgravity provides us with an accelerated model of the diseases. So animal models in combination with microgravity will enable us to study musculoskeletal diseases, inflammation and wound healing."

This investigation was sponsored for the ISS National Laboratory, developed in partnership with Novartis Institute for Biomedical Research, BioServe, Houston Methodist Research Institute and NASA Ames Research Center.

Rodent Habitat module with both access doors open.

Image credits: NASA/Dominic Hart

The Small Satellite Revolution

The modern Small Satellite—SmallSat—revolution began in the 1990s with advances in low-power, highly integrated and lightweight microelectronics. SmallSats offer many advantages over their large, conventional counterparts, including simplified development, relative ease of construction and testing, and lower launch costs. Through a concerted program of investment and development, NASA and the International Space Station (ISS) were instrumental in building a fledgling technical approach for SmallSat deployment into a sustainable and growing market.

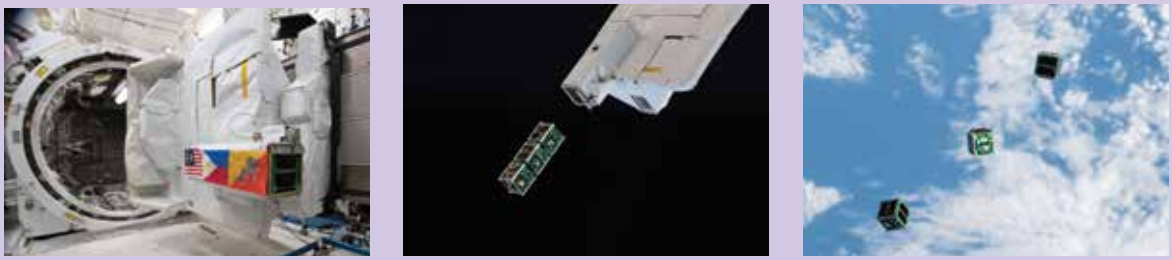
Small to Big: Enabling a Growing SmallSat Marketplace

Direct ISS involvement with a specialized form of small satellites, known as CubeSats, began in 2012 when the Japanese Kibo module deployed its first CubeSat. A CubeSat is a SmallSat designed to specific standards that were developed by the California Polytechnic State and Stanford Universities. The CubeSat has come to dominate the SmallSat market, representing 87% of all SmallSats launched as of 2017. CubeSats are built to standard dimensions (Units or "U") of 10 x 10 x 10 centimeters (~4 x 4 x 4 inches). They can be 1U, 2U, 3U or 6U in size, and typically weigh less than 1.33 kilograms (3 pounds) per U.

CubeSats are a relatively recent development, with the first-ever CubeSat launched in 2003. It took nearly a decade for the CubeSat form to catch on, with only 23 CubeSat launches for the entire year in 2012. However, following completion of ISS assembly in 2011, launch rates have increased dramatically. Indeed, between 2012 and 2017 more than 200 CubeSats were launched from the ISS alone. Worldwide, more than 725 CubeSats were launched in that period,with the rate of launch growing by 66% per year.

The CubeSat has come to dominate the SmallSat market, representing 87% of all SmallSats launched as of 2017.

The first CubeSats deployed from the ISS did so through the capabilities of the Japan Aerospace Exploration Agency's (JAXA's) Kibo module. Kibo's unique capabilities include an airlock system and a robotic arm. The first orbital deployment of CubeSats from Kibo was successfully conducted in October 2012 through the Small Satellite Orbital Deployer (J-SSOD) developed by JAXA. The J-SSOD is capable



BIRDS-2 deployed from the Japanese Experiment Module (JEM). From left to right: JEM airlock slide table with BIRDS-2 CubeSats representing Bhutan, Malaysia, and the Philippines, ready for deployment (July 30, 2018); BIRDS-2 satellite deployment from the JEM Small Satellite Orbital Deployer (August 10, 2018); BIRDS-2 satellites following deployment.

Image credit: NASA

of launching 6U in CubeSats per airlock cycle. There are 10 Kibo Module airlock cycles scheduled each year that support not only CubeSats, but many other external payloads as well.

Since 2012, nano-satellites and CubeSats from many countries around the world have been deployed from Kibo. On many occasions these CubeSats represent the first satellites designed and built by students or engineers from these countries. The KiboCUBE program, initiated in 2015, is a collaboration between the United Nations Office for Outer Space Affairs and JAXA in utilizing the ISS Kibo for the world. KiboCUBE aims to provide educational or research institutions from developing countries of United Nations membership with opportunities to deploy, from the ISS Kibo, CubeSats that they develop and manufacture. Through KiboCUBE, a CubeSat from Kenya has been deployed. The KiboCUBE program was extended from September 2018 to March 2021, with the Republic of Mauritius selected as the next country to participate.

CubeSat missions benefit Earth in varying ways. The ISS has continued to serve as a test bed for novel CubeSat technologies today. For example, the 2018 Radix mission, developed by Analytical Space, Inc., is intended to demonstrate the operation of the first commercial optical communication downlink.

Photography—From Another "Planet" to Ours

Started by three NASA engineers in 2010, Planet provides Earth observation photography from low-Earth orbit. Using the space station as a technology development test bed, Planet deployed 110 small satellites before moving on to using commercial launch providers. Since its formation, Planet has garnered $183.1 million of private funding and secured two contracts with National Geospatial Intelligence Agency, worth a combined $34 million. With an estimated annual revenue of $64.4 million, and value of over $1 billion, Planet operates a fleet of more than 175 satellites and employs more than 470 people as of 2018.

The Radix service downlinks data to the ground using laser communication, and increases the amount of data that may be transmitted for current and future satellite users. The ability for satellite operators to downlink more data improves the function of applications that are important on Earth, such as real-time weather monitoring, crop monitoring and global climate monitoring. This greatly increases Earth observation and monitoring science provided to scientific and commercial users.

RainCube, developed by Tyvak Nano-Satellite Systems Inc. in collaboration with NASA's Jet Propulsion Laboratory, is another technology demonstration mission taking place in 2018. This CubeSat will be the first to use a radar instrument. RainCube will enable precipitation radar technologies on a low-cost, quick-turnaround platform, demonstrating a small radar and ultra-compact deployable antenna and providing a profile of the Earth's vertically falling precipitation such as rain and snow. The RainCube mission enables future Earth science missions to improve weather and climate models.

In late 2017, the Integrated Solar Array and Reflectarray Antenna (ISARA) demonstrated a new hybrid antenna and power system for use in CubeSats. Advances in material science and electrical engineering have made possible a flexible solar panel that can send and receive messages. ISARA, developed by The Aerospace Corporation and NASA's Jet Propulsion Laboratory, tested the performance of these new solar antennas in collecting instrumental data aboard a CubeSat deployed from the ISS and monitored by ground-based engineering crews.

From satellites that focus on technology demonstrations to test data transmission rates and increase efficiency, to Earth observation satellites that help scientists explore our planet's atmosphere, the variety of science enabled by CubeSats results in diverse benefits and opportunities for discovery and commercial application.

SmallSats were once the exclusive domain of research institutes and universities. Today, 51% of SmallSats are being developed by the private sector, and 67% of all SmallSats are developed to provide commercial services. Of note, 90% of all commercial SmallSats built between 2012 and 2017 were manufactured by U.S.-based companies. ISS-based CubeSat deployment, along with various NASA/ISS programs and initiatives, helped demonstrate how a new platform could foster a dramatic disruption that reinvigorated an established market. In that sense, the ISS performed its mission well—to be an innovator and a locus for experimentation.

Jumpstarting the CubeSat Revolution*

**Part of this article is reprinted with permission from Upwards Magazine (V3.1),*

As of August 2018, more than 200 CubeSats (i.e., small satellites traditionally measuring 10 x 10 x 10 centimeters [~4 x 4 x 4 inches]) have launched from the ISS into low-Earth orbit (LEO). The majority of these have been deployed by NanoRacks, a commercial service provider that supports customers using the ISS U.S. National Laboratory as a platform for both SmallSat launch and research and technology development (R&D) on the interior and exterior of the ISS.

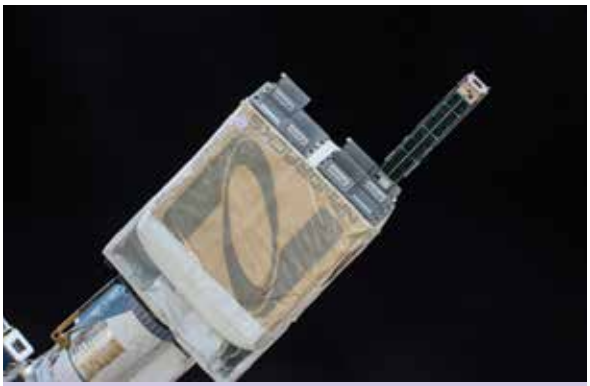
With growing interest in CubeSats from academia and industry, NanoRacks, in 2013, became the first commercial entity to utilize the ISS as a platform for CubeSat deployment using the J-SSOD. Following this early deployment, NanoRacks self-funded its own ISS deployer to expand beyond the 6U capacity of the J-SSOD in order to use the maximum capacity of the JEM airlock. The resulting NanoRacks CubeSat Deployer uses two airlock cycles, each holding eight deployers. Each deployer is capable of holding 6U, allowing a total of 48U per airlock cycle.

NASA astronaut Jack Fischer loads the NanoRacks CubeSat Deployer into an airlock in the JEM on the ISS on May 15, 2017. Ground crews took control when the deployer was transferred to the outside of the space station, triggering deployment of the satellites into Earth orbit.

Image credit: NASA

The ability of companies like NanoRacks and their advanced technologies to meet future demand for launch platform capabilities is critical.

NanoRacks' assessment of market demand for CubeSat deployments proved accurate. Between 2014 and 2017, NanoRacks deployed 176 CubeSats, thereby demonstrating that the market for high-capacity deployment was strong. Taking advantage of the commercial resupply vehicles used for ISS operations, NanoRacks further expanded CubeSat launch deployment capabilities by developing the External NanoRacks Cygnus Deployer (ENRCSD). This deployer is installed on the exterior of the Cygnus service module, and is capable of deploying up to 36U of satellites after Cygnus' completion of its primary space station resupply mission. Not only does this increase the capacity for CubeSat deployments, it allows for deployment in orbits up to 499 kilometers (310 miles), about 96 to 145 kilometers (60 to 90 miles) higher than the ISS. In August 2018, NanoRacks announced the successful deployment of six CubeSats from its fifth



The NanoRacks CubeSat Deployer "ejects" the Spacecraft for High Accuracy Radar Calibrationa microsatellite into orbit from the ISS on May 15, 2017.

Image credit: NASA

ENRCDS mission, bringing the overall total of CubeSats deployed through NanoRacks systems to 223.

"Small satellites are helping democratize the use of space," said NanoRacks CEO Jeff Manber.

CubeSats are cheaper and lighter, therefore getting them into orbit is easier and less risky. As the size and cost of increasingly capable electronics shrink, SmallSats are becoming just as capable as their larger predecessors for certain applications. They also do not require the cost of a dedicated launch vehicle, which is needed by larger satellites.

Jenny Barna, director of launch at Spire Global, a satellite-powered data company, noted that the certainty and timing of launches is a barrier in the SmallSat industry. Spire currently has 58 SmallSats in orbit, more than a quarter of which were launched from the ISS or visiting vehicles through NanoRacks. Spire plans to continue growing the size of their constellation in 2018. Barna recalled how there was a global shortage of rideshare opportunities in 2015 and 2016, especially for commercial satellites.

"We had raised sufficient funding by the summer of 2014 and were expected to have the initial constellation up by the end of 2015, but all launches were extremely delayed, leaving new businesses like ours struggling to move forward," said Barna. "Access through NanoRacks and the space station helped us get part of the way there and showed our investors and potential customers that our technology worked."

By making deployment accessible to so many people, the ISS has helped create a new space industry, sparked commercial innovation, and enabled new research and scientific discoveries. Remote sensing data from SmallSats is used in the oil and gas, mining, fishing and other industries, and for atmospheric science and humanitarian applications such as disaster response and search-and-rescue missions. For example, Spire's satellites monitor weather and marine and air traffic. Moreover, telecommunication capabilities within satellites may enable technologies and services such as global Wi-Fi and advanced GPS.

The ISS National Lab's ability to accelerate R&D and technology demonstrations in this sector by serving as a reliable launchpad is a powerful catalyst for innovation. "We've reached this wonderful moment where space is playing a role helping us here on Earth," said Manber.

Dozens of ISS National Lab payloads over the last few years have signaled rapid growth in interest and innovation from the SmallSat community. In 2016, NanoRacks completed the first-ever SmallSat launch to reach an altitude higher than that of the ISS and repeated this feat in 2017. In 2017, they also launched the QB50 payload, a constellation of 28 CubeSats—developed through a European Union Commission collaboration with academic and research institutes from 23 countries—designed to study the upper reaches of the Earth's atmosphere.

"The ISS has become critical as a platform for research in microgravity and in the LEO space environment, as a proving ground for human space exploration, and now as a launch platform for small satellites," said Benjamin Malphrus, director of Morehead State's Space Science Center, which has also launched multiple NanoRacks-supported ISS National Lab payloads in recent years.

For example, the Cosmic X-Ray Background Nanosatellite launched in 2017 is a CubeSat designed and built by Morehead State that has the potential to give astrophysicists the most precise measurements ever made of the cosmic background X-ray radiation that occupies space between galaxies—putting together an accurate picture of the evolution of the early universe, which has implications for fundamental physics and beyond.

Similarly, the Dependable Multiprocessor experiment (DM-7), launched in 2016 and developed by Morehead State University and Honeywell International, Inc., validated the design of a new payload processor for use in SmallSats and other spacecraft. DM-7 is a miniature parallel processor that harnesses the processing power of commercial off-the-shelf technology to benefit science and may ultimately allow companies to do more processing on spacecraft and reduce requirements for raw data transmission to the ground. Moreover, with middleware from Honeywell, the DM-7 processor costs between $20,000 and $30,000, compared with current processors today that are in the $250,000 range.

Various related payloads addressing the need for advanced technologies within spacecraft include ISS National Lab projects from Hewlett Packard Enterprise, Business Integra Technology Solutions, Yosemite Space, and others, including a project from NovaWurks in 2017, which pioneered a concept to assemble larger satellites from small, independent components separately delivered to the ISS and then assembled in orbit by the astronaut crew.

Manber notes that the number of ISS users interested in SmallSat deployment continues to grow and includes new space firms such as Spire, research universities such as Morehead State, and government agencies

such as the U.S. Department of Defense. This is consistent with trends above and below LEO, as small satellites for observing conditions on Earth are the fastest-growing segment of the $260.5 billion global satellite industry, according to an annual report issued by the Satellite Industry Association. Additionally, SpaceWorks' 2017 market assessment expects microsatellite launches to grow 10% annually over the next 6 years.

Recognizing the need for a greater capacity of CubeSat launches from the ISS and the capability to launch larger payloads, NanoRacks plans to deploy the first commercially owned airlock on the ISS in 2019. Currently, the Japan Aerospace Exploration Agency (JAXA) operates the only airlock on the space station for transferring payloads from the interior to the exterior of the ISS. The airlock is relatively small and opens only 10 times a year, with five of those openings allocated to JAXA.

The new commercial NanoRacks Airlock Module will have five times more capacity than the JAXA-operated airlock and will accommodate larger satellites (up to 150 kilograms [330 pounds). It also will be able to deploy multiple SmallSats at once, something not possible with the current airlock. Once the new airlock is installed, ISS crew members will be able to assemble payloads in orbit using parts sent to the ISS in cargo transfer bags.

In addition to serving current customer needs, the NanoRacks commercial airlock's modular design (the "Gateway to Space") sets the stage for the design of future satellite deployment platforms that will serve the commercial sector in a post-ISS era. NanoRacks is partnering with Boeing and Thales Alenia Space on manufacturing key parts of their airlock module. The outside of the airlock also offers access to power and Wi-Fi communications for externally mounted payloads, which is of interest to commercial and government customers. "For us, this is a stepping stone to having our own space station," Manber said.

Manber predicts that the industry will continue to move toward slightly larger and more capable SmallSats, with commercial customers, universities, and governments leveraging the lower cost and rapid development cycle from design to deployment that they offer compared to large monolithic spacecraft. "I think it will go beyond LEO, and we are going to begin to see SmallSats used in deep space and on planetary missions," he said.

The ability of companies like NanoRacks and their advanced technologies to meet future demand for launch platform capabilities is critical. International partners have expressed strong interest in extending LEO platform operations beyond the current ISS funding end date of 2024. The most viable path forward for government or private sector parties is a next-generation, newly constructed space station. Even as questions about what comes after the ISS continue to be debated, one thing is clear: SmallSats are here to stay.

The Kestrel Eye IIM (KE2M) CubeSat is pictured shortly after it was deployed from the tip of the Dextre attached to the Mobile Servicing System on October 24, 2017. The KE2M is carrying an optical imaging system payload that is being used to validate the concept of using microsatellites in LEO to support critical operations.

Image credit: NASA

Tropical Cyclone in Sight*

**Part of this article is reprinted with permission from Upwards Magazine (V3.1),*

Tropical cyclones, also known as hurricanes and typhoons, are the most destructive natural forces on Earth—causing an estimated 10,000 deaths and $26 billion in property damage worldwide each year. In recent decades, scientists have become much better at predicting where these storms might hit and how powerful they will be. However, as seen with Hurricane Katrina and many others, initial predictions can be off, leading to terrible consequences for the affected communities.

Improved measurements and predictions of tropical cyclone intensity and trajectory would help communities

The ISS National Lab provides a unique platform for monitoring tropical cyclones because its orbit covers virtually all the regions where tropical cyclones are found.

better prepare for such storms. Providing such measurements is the aim of an ISS National Lab project by Visidyne, Inc. called Cyclone Intensity Measurements from the ISS (CyMISS). The CyMISS project is using the unique vantage point of LEO to measure the most intense area outside a tropical cyclone's eye, called the eyewall. Towering eyewall clouds are the strongest indicators of storm intensity and trajectory, and higher-accuracy measurements of the altitudes of these clouds could lead to better predictions of a storm's path and strength, explained A.T. Stair, president of Visidyne and co-investigator for CyMISS.

"Our objective is to obtain high-resolution measurements of several tropical cyclones that are Category 3 and higher," said Stair. "And we now have a very good collection of almost a dozen of them."

Building on the success of the CyMISS project, Visidyne has started a new commercial company called Trans World Analytics, Inc. (TWAI). The company will first use high-altitude, solar-powered vehicles, followed by microsatellites, to characterize tropical cyclone eyewall clouds and measure storm intensities, with the goal of achieving lifesaving advancements in global knowledge about these devastating storms.

The United States currently tracks tropical cyclones using a combination of satellite imagery, Doppler radar, and hurricane hunter aircraft. Weather monitoring satellites, which have been in use since the 1960s, are helpful in tracking storm development over the ocean and predicting surface tracks using sequences of images. Meteorologists use Doppler radar to detect

Hurricane Florence as photographed from the ISS on September 10, 2018.
Image credit: NASA

rain, forecast the strength and location of rain bands, measure wind speed and direction, and predict rainfall totals. Although these technologies are helpful in collecting information about storms, the most accurate tropical cyclone information is gathered using reconnaissance aircraft called hurricane hunters.

Hurricane hunter aircraft are operated by the U.S. Air Force out of Biloxi, Mississippi, and by the National Oceanic and Atmospheric Administration (NOAA) out of Tampa, Florida. These operations rely on flying specialized aircraft directly into tropical cyclones at low altitudes (between 152 and 3048 meters [500 and 10,000 feet]) to gather critical information about the storms, such as their central pressure, eye location, wind speeds and overall size. This method results in accurate forecasting, but it is also extremely expensive and potentially dangerous. Six hurricane hunter aircraft and their crews (a total of 53 lives) were lost between 1945, when flights began, and 1974.

Given the hefty price tag, no other country in the world sends hurricane hunters into tropical cyclones. Instead, nearby countries use forecasts based on U.S. hurricane hunter data. More-distant nations rely on warnings issued by the Joint Typhoon Warning Center in Pearl Harbor, Hawaii, which uses a technique called the Dvorak method. Developed in the 1970s, this method uses photographs from weather satellites to analyze the overall cloud pattern of a tropical cyclone and make predictions based on that pattern.

However, the Dvorak method is somewhat rudimentary, according to Paul C. Joss, professor of physics emeritus at the Massachusetts Institute of Technology (MIT) and principal investigator of CyMISS. The method's predictions are based on the assumption that storms with the same cloud patterns will have the same intensity and have no underpinnings in atmospheric physics.

"The Dvorak method is subject to very large errors," Joss said, "yet that's the best that most of the world can depend on."

Visidyne's commercial spin-off, TWAI, will focus on closing this gap. Joss said the primary goal is to increase coverage and forecast accuracy of tropical cyclone intensities and surface tracks for countries such as India, Australia, Japan and the Philippines, which do not have hurricane tracking systems like the one used in the United States.

The origins of the CyMISS project trace back to the early 1990s as a joint effort between Russia and the United States to measure tropical cyclone intensities. Unfortunately, this project was discontinued in 2004 amid a sharp decrease in cooperative projects with Russia. Visidyne began seeking alternative sources of funding. After securing a grant from the ISS National Laboratory in 2013, Visidyne began to study tropical cyclones using high-resolution photos taken by fixed cameras onboard the ISS.

The ISS National Lab provides a unique platform for monitoring tropical cyclones because its orbit covers virtually all the regions where tropical cyclones are found. This comprehensive coverage from LEO enables accurate storm measurements from the Pacific Rim and Australia to the Arabian Peninsula and east Africa, where U.S. hurricane hunters do not fly.

Visidyne can determine the relative altitude of eyewall clouds by applying a photographic technique known as parallax to sequences of high-resolution images taken from the ISS. Using this technique, two photographs of the same object are taken at slightly different angles and pieced together to measure depth. This allows CyMISS researchers to create three-dimensional images, which they can use to accurately measure the altitudes above sea level of the storm's cloud features.

CyMISS researchers use these and other data to measure the intensity of a tropical cyclone using a complex method that analyzes eyewall cloud altitudes and temperatures in the context of independently available sea-surface temperature data. By applying the laws of thermodynamics, researchers use this information to derive a formula that measures the storm's central sea-level pressure with higher accuracy than other remote-sensing techniques.

Central sea-level pressure is the most critical component in determining a tropical cyclone's strength. Accurate measurement of this quantity allows scientists to determine the peak sustained winds in a well-developed tropical cyclone to within 10 mph. Real-time updates of the central pressure of a tropical cyclone are also key to forecasting its future intensity changes and surface track. This technique is expected to be most accurate and reliable for the most powerful and dangerous storms, with intensities of Category 3 or higher.

TWAI aims to build on the success of the CyMISS project and further develop techniques for accurately monitoring and predicting the intensities and tracks of tropical cyclones on a global scale. The goals are to use remote sensing methods that will provide cost-effective, worldwide coverage of tropical cyclone intensities with accuracies comparable to those attained with hurricane hunter aircraft for the United States and adjacent countries, and to supplement the data gathered

by hurricane hunters for improved forecasting of storms that impact the United States. To do this, TWAI hopes to deploy a small constellation of microsatellites in LEO.

The implications of such an approach are exciting, given that most regions of the world cannot afford the use of hurricane hunter aircraft. However, given the high cost of deploying a constellation of microsatellites, TWAI first intends to use high-altitude vehicles called Solar Falcons™ to optimize the data acquisition techniques developed by CyMISS onboard the ISS, and to use these techniques for improving tropical cyclone measurements and forecasts worldwide.

Designed to fly at 19,812 meters (65,000 feet), the Solar Falcons™ resemble uncrewed airships but are much lighter and more durable. They are solar powered, capable of reaching speeds around 129 kilometers per hour (80 miles per hour), and can remain in flight for weeks at a time, following tropical cyclones throughout the storms' lifetimes. In addition to measuring cloud altitudes within a tropical cyclone's eyewall, the Solar Falcons™ will also be able to track the storms at night and measure cloud temperatures using infrared cameras—two limitations researchers were not able to address through CyMISS.

Once operational, the Solar Falcons™ could provide an unprecedented range of coverage, needing only five ground sites to obtain nearly global coverage of tropical cyclones: two for North America, and three to cover the Western Pacific rim, Australia, and the Indian Ocean. "It's a way of getting started at a much lower price point," said Joss.

Although the Solar Falcons™ will not be able to provide continuous worldwide coverage of all tropical cyclones as can microsatellites, this intermediate step will enable better measurements of storm intensity and improved predictions of landfall location and storm strength at the time of landfall. A Solar Falcon™ will also be able to hover in place over the landfall site, thus allowing scientists to better determine the nature and extent of damage following a storm. If all goes as planned, TWAI hopes to launch its first Solar Falcon™ by the end of 2019.

"The CyMISS project is an important first step toward closing the gap in accurate and reliable global forecasting of tropical cyclones," said Joss. "Higher-accuracy predictions could potentially save countless lives and help to significantly reduce the property damage resulting from these devastating storms."

Keeping an Eye on Algae from Space

At the coast, people typically expect blue ocean waters and white sand beaches. They may "see red" if things look green instead.

Harmful Algal Blooms (HABs)—abnormal proliferation of algae in coastal environments—threaten human health and marine life. Coastal business, recreation and tourism industries suffer, as thick layers of smelly foam form on beaches and local seafood becomes suspect.

The natural world suffers, as well. Fish and other creatures, including endangered marine mammals, may die. Algae play a major role in the global carbon cycle, and blooms are responsible for much of the ocean carbon fixation.

Now, scientists have developed a way to detect HABs early on by using images from space.

Detecting HABs presents a challenge due to the complexity of the coastal environment, with its various water types and depths, dissolved and suspended organic and inorganic matters, and bottom reflectance. Conventional algorithms detect chlorophyll, a green pigment in algae, and cannot discriminate between an actual bloom and other bloom-like features such as sediment plumes or colored dissolved organic matter.

The HAB system uses an algorithm that instead detects chlorophyll fluorescence, which allows it to discriminate blooms from these other features.

A former Naval Research Laboratory scientist, Ruhul Amin, refined the algorithm as part of an ISS National Lab project. Due to its altitude and inclination of orbit, the space station covers about 80% of the Earth's surface, including all tropical and most temperate coastal regions where HABs are a major threat. That made it an ideal platform for coastal HAB studies.

"Using the refined algorithm, we successfully detected seasonal formation of HABs off the Gulf Coast of

Harmful Algal Blooms (HABs)—abnormal proliferation of algae in coastal environments—threaten human health and marine life.

Florida," said Amin. "HABs in the Gulf, particularly those on the West Florida Shelf, cause millions of dollars in socioeconomic damage each year, threatening marine life and human health."

Amin formed a spin-off company, BioOptoSense, LLC, based on this work. "The algorithm also may help us understand environmental processes that contribute to HABs, ultimately benefiting human health and the multibillion-dollar fishing and tourism industries," he adds. The University of Mississippi, City College of New York and the Naval Research Laboratory have already used the BioOptoSense algorithm.

Images used to develop the algorithm initially came from the Hyperspectral Imager for the Coastal Ocean (HICO) onboard the space station. This special camera separated light into hundreds of wavelength channels, revealing information about the composition of water and land along the coasts. HICO collected approximately 10,000 hyperspectral scenes of Earth, most of them available through NASA's Ocean Color website.

HICO is no longer operating; however, the HAB algorithm can use images from satellite sensors such as Sentinel-3 and the Geostationary Ocean Color Imager.

Because HABs usually occur when water temperatures are warm, the problem may grow as climate change causes warmer waters around the globe.

By providing reliable, precise locations, the HAB system potentially could represent significant cost savings for coastal managers and organizations that routinely send out sampling boats to collect HAB data. These field measurements are labor intensive, time consuming, and very costly. This tool also allows coastal businesses such as tourism operators to minimize the economic hit from a HAB by preparing for a bloom before it reaches the shore. Tourists can use this information to plan their trips. Scientists studying the ecology of HABs can target locations for field measurements based on the actual presence of a HAB.

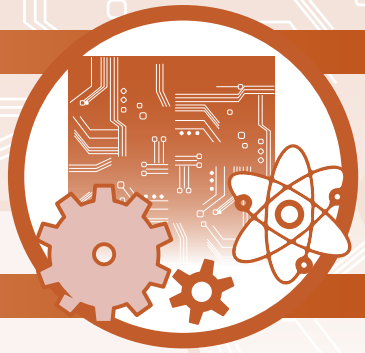
"Furthermore, this work will lead to improvements in regional biochemical models by, for example, enabling addition of a HAB component as a state variable in regional ecosystem models," said Amin. "That facilitates assimilation of bloom imagery into the models to improve bloom predictions."

Watching for green from space could help keep beachgoers, and others, in the pink.

Algae bloom in Lake Erie as seen from the ISS.
Image credit: NASA

ROBO/EVA Training in the Virtual Reality (VR) Lab with Expedition 58 crew David Saint-Jacques.
Image credit: NASA

Innovative Technology



In space, physical processes can be better understood with the control of external influences such as gravity. Technical innovations designed for space systems are tested on the International Space Station (ISS) before use in other spacecraft systems. Unexpected discoveries are possible while investigating how new technologies operate in space. Simplified physical systems can also be directly used to improve models of physical processes leading to new industrial techniques and materials.

The ISS provides the unique capability to perform long-duration experiments in the absence of gravity and in interaction with other spacecraft systems not available in any other laboratory. Additional insight comes from the presence of the ISS crew observing and interacting with these experiments and participating in the discovery process.

The ISS research portfolio includes many engineering and technology investigations designed to take advantage of these opportunities. Experiments that investigate thermal processes, nanostructures, fluids and other physical characteristics are taking place to develop these technologies and provide new innovations in those fields. Additionally, advanced engineering activities that are operating in the space station infrastructure prove next-generation space systems increase capabilities and decrease risks to future missions. Emerging materials, technology and engineering research activities on the ISS are developing into benefits for economic development and quality of life on Earth.

Fluids and Clean Water

Whether in the vacuum of space or the relative comfort of the Earth's surface, access to clean water is essential for living organisms. The challenges of moving and processing fluids such as water using compact, reliable systems in the microgravity environment of space have led to advances in the way we purify water sources on the ground. Testing methods developed to ensure water quality on the International Space Station (ISS) have led to advancements in water monitoring here on Earth. Investigations into the basic dynamics of how fluids move in space have also led to advances in medical diagnostic devices.

More Efficient, Lightweight Water Filtration Technologies in Space and on Earth

A safe living environment for astronauts in space is essential. On future human exploration missions, improved technologies including biologically regenerative life support systems will provide a means to reduce and optimize upload mass and hence have a positive effect on mission costs. In September 2015, an important technology experiment supported by the European Space Agency (ESA) was performed for the first time with promising test results. This experiment tested the efficiency of a forward osmosis biomimetic membrane technology to filter certain semi-volatile substances from ISS condensate and confirm that it exceeds the filtration performance of current ISS water recovery systems. Forward osmosis technologies offer a far more resource-efficient means of filtration compared to the more common reverse osmosis techniques. The successful testing of this membrane provides a more resource-efficient means to filter/reclaim water in space (and on Earth). This would help reduce upload mass of expendable media currently used in water processing on the ISS, and holds a promising technology for use on future exploration missions where resupply of expendable media is not a viable option. The membrane can potentially achieve a water permeability two orders of magnitude higher compared to existing reverse osmosis membranes on Earth, thus implying a great application on Earth with respect to fresh water supply through desalination of seawater and brackish water.

The Aquaporin Space Alliance (ASA) is commercializing the patented Aquaporin Inside™ technology in space applications and space programs together with European and U.S.-based entities. ASA is a joint venture company created by Aquaporin A/S and Danish Aerospace Company ApS.

Forward osmosis technologies offer a far more resource-efficient means of filtration compared to the more common reverse osmosis techniques.

ESA astronaut Andreas Mogensen working on the AquaMembrane experiment.

Image credit: ESA and NASA

New Technologies Give Tap Water, and Other Markets, the "Treatment"

A European Space Agency-sponsored International Space Station water recovery investigation has helped the Aquaporin Space Alliance and its parent company to commercialize the Aquaporin Inside™ technology for ground-based applications. This and other Aquaporin activities have resulted in seven patents and consideration in multiple scientific journals. In 2016, Aquaporin reported $1.35 million in revenue as a result of commercializing the Aquaporin Inside Tap Water Reverse Osmosis membrane for household purifiers. Their recently developed production facility will be used to launch several more products into the advanced water treatment, food and beverage, and desalination markets. These products include a Brackish Water Reverse Osmosis, Seawater Reverse Osmosis, and Forward Osmosis membranes, which were, as of June 2017, in lab and pilot-scale production.

Advanced NASA Technology Supports Water Purification Efforts Worldwide

Whether in the confines of the ISS or in a tiny village in sub-Saharan Africa, drinkable water is vital for human survival. Unfortunately, many people around the world lack access to clean water. At-risk areas can gain access to advanced water filtration and purification systems through technology that was developed for the space station, thereby making a lifesaving difference in these communities.

The first of many ground-based water filtration systems using NASA technology was installed in northern Iraq in 2006. The system was developed by Water Security Corporation (WSC) (**http://www.watseco.com/**) in Reno, Nevada. A nonprofit organization, Concern for Kids, had learned about a well failure that left the residents of Kendala, Iraq, without access to drinkable water. The population of the village quickly dwindled from 1,000 residents to a mere 150. Those who remained were forced to use a nearby creek that contained water that had been contaminated by livestock.

Todd Harrison, then president of Concern for Kids' board of directors, set out on a mission to revive the ailing community. The solution came in the form of a familial connection that put Harrison in touch with the NASA engineers who developed technology to provide clean water aboard the space station.

Harrison's sister, Robyn Gatens, was the engineering manager for the Environmental Control and Life Support System (ECLSS) project at NASA's Marshall Space Flight Center. She and her team of engineers developed the cutting-edge system that recycles air and water aboard the space station.

Efficiently recycling wastewater onboard the ISS reduces the need to provide the resource via resupply. Without this capability, the space station's current logistics resupply capacity would not be able to support the standard six-crew-member population, and resupply is not even an option for long-duration space travel.

Two principal components make up the space station's regenerative ECLSS: The Water Recovery System (WRS) and the Oxygen Generation System (OGS). The WRS conducts the water purification and filtration process in the ECLSS. WSC licensed this technology to adapt it to an Earth-based water treatment system.

Harrison discovered an interesting relationship between WSC's water filtration system and NASA's system because of his familiarity with his sister's work. NASA's previous research and application resulted in the creation of the Microbial Check Valve (MCV), an integral component of the purification and filtration process.

The MCV is an iodinated resin that provides a simple way to control microbial growth in water without the use of power. It performs an important secondary nutritional function for the populace by dispensing iodine into

At-risk areas can gain access to advanced water filtration and purification systems through technology that was developed for the space station, thereby making a lifesaving difference in these communities.

Filtration system providing clean, safe water installed at a school in Chiapas, Mexico.

Image credit: Sinergia Systemas

the water. When added to the diet, iodine promotes proper brain function and helps maintain levels of hormones that regulate cell development and growth. Children born in iodine-deficient areas are at risk of neurological disorders and mental retardation.

With the help of U.S. Army Civil Affairs and Psychological Operations Command (Airborne) personnel, a 2,000-liter water tank and fresh water were delivered to the village in Iraq. Workers ensured that the water was clean and iodinated to prevent bacteria and virus contamination.

Since that initial effort, the commercialization of this NASA technology has provided aid and disaster relief for communities worldwide. WSC owns the rights to NASA's iodinated resin water purification technology and has enhanced and adapted it for affordable and easy-to-use water purification products. The company has installed systems around the world, including home water purifiers in India; village processing systems in remote areas of Mexico, Central, and South America; water bottle filling stations in Pakistan; and even a survival bag designed as a first response device for natural disasters, refugee camps, civil emergencies and remote locations.

These kinds of joint collaborations show how effectively space research can adapt to contribute answers to global problems.

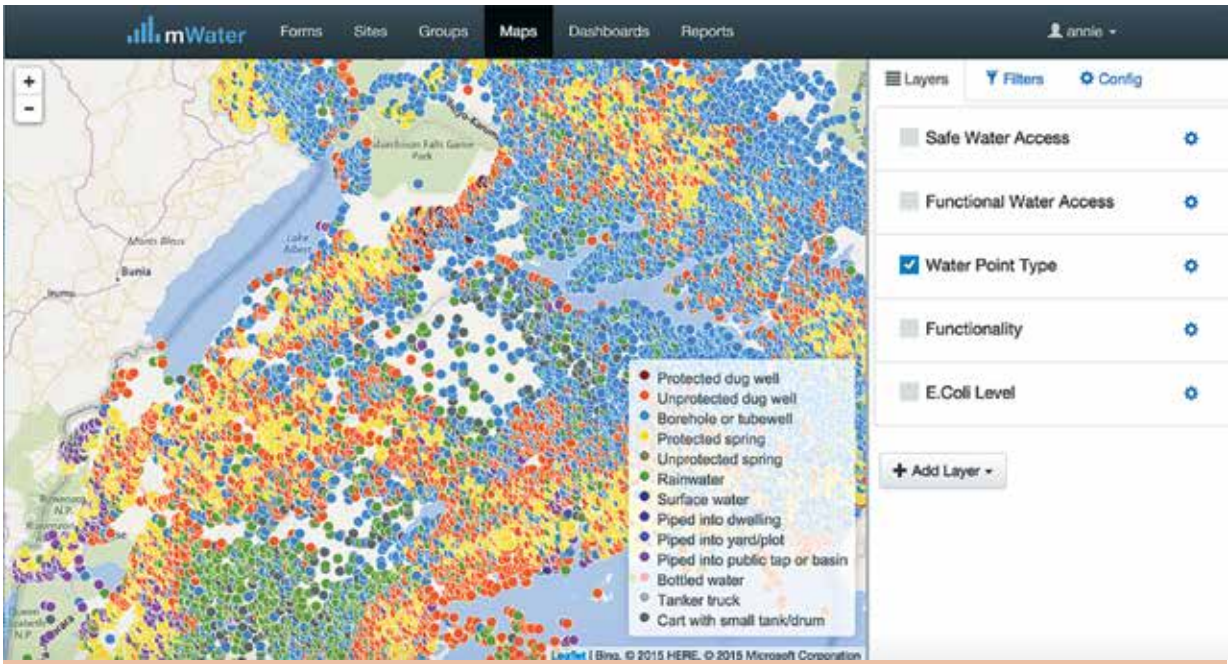
Space Station-Inspired mWater App Identifies Healthy Water Sources

What if that clear, sparkling stream of water coming from the ground or a faucet were teeming with contaminants? How would you know? Whether you live in some remote region of Africa, a high-rise in New York City or onboard an orbiting laboratory in space, you need reliable drinking water to survive. Now, you can check the cleanliness of your water using a phone app.

This handy tool, based in part on ISS technology, provides a global resource that is available for free download as an app or usable via the Web browser version on most smartphones. Governments, health workers and the public can make use of the mWater app (**http://www.mwater.co/**) to record and share water test results. During the first year of beta release, more than 1,000 users downloaded mWater and mapped several thousand water sources. Currently, mWater is used by more than 25,000 government, non-profit and academic institutions in 147 countries.

John Feighery, mWater co-founder and former lead engineer for air and water monitoring with NASA, was inspired by his work for the space station. There, he and his team created efficient, mobile and ambient testing techniques to test for contamination in drinking water sources without the need for costly lab

Whether you live in some remote region of Africa, a high-rise in New York City or onboard an orbiting laboratory in space, you need reliable drinking water to survive.



Visualization of public water points in East Africa that have been shared by mWater users from across the globe. Users can map and monitor water points and other critical infrastructure using the free mobile app and data portal.

Image credit: mWater

equipment such as incubators. The resulting Microbial Water Analysis Kit (MWAK)—part of the environmental monitoring Crew Health Care System Environmental Health System (CHeCS EHS) suite onboard the space station—sparked Feighery's imagination, thus providing the basis for the mWater testing of E. coli in 100-milliliter (3.38-ounce) water samples.

One key innovation that came from NASA was proving that these types of tests will work at near-ambient temperatures. Various studies have shown that any temperature around 25°C (77°F) will produce a result, whereas traditional laboratory procedures call for incubation at 37°C (98.6°F). This is crucial for developing countries because incubators are expensive and require reliable electricity, and they can easily break down. Since many of the countries that suffer from poor access to safe water are tropical, the tests can easily be done at room temperature, by anyone, most any time of the year.

While volunteering with Engineers Without Borders in El Salvador, Feighery discovered that hefting testing materials or expensive equipment to test water sources is unrealistic. Technologies bound for the defined real estate of the space station aim for portability, affordability and effectiveness, and must also work well in remote or low-resource regions of the world. The mWater test supplies cost users only $10 per kit.

Combining his aerospace experience and philanthropic passions, Feighery worked with co-founder and wife Annie Feighery on what became mWater. The app was developed following the 2011 Water Hackthons (**https://open.nasa.gov/blog/waterhackathon/**), and improved through field testing sponsored by U.N. Habitat. The app helps to simplify the recording of water quality results, the mapping of water sources, and the identification of safe water nearby. What began as a simple app for monitoring water quality data has grown into a full-featured mobile collection and visualization platform for almost any kind of data.

The tests and app were both designed with ease of use in mind. The user tests the water, allows the test to incubate at ambient temperatures, photographs the results to count the bacteria and finally uploads the findings to the global water database.

Testing—and Verifying—the Waters

Founded by researchers behind NASA's Microbial Water Analysis Kit (part of the space station's environmental control systems), mWater is a non-profit venture focused on providing low-cost test kits and monitoring software in support of the global Water and Sanitation for Health (WASH) initiative. Currently, mWater is the largest WASH access database on the planet. Based on space station technology, the mWater testing kit costs $10 and uses efficient, mobile techniques to test for contamination in drinking water sources. The accompanying mobile applications receive more than 70,000 submissions per month, and enable the public to record water quality and map safe water sources.

Feighery's experience writing crew procedures at NASA influenced the design of the app, which is task-oriented and designed to require very little training beyond following the procedure. In the future, the mWater team plans to introduce checklists for each type of water test to further improve ease of use and reduce the training needed to perform field testing.

Test results upload to the cloud-based global water database using a phone's Global Positioning System to identify the exact location of the water source. Each location gets a unique and permanent numeric identifier for reference by those who visit the global water source map for updates. Users can add new water location points and input or update test results, thereby working within the open source sharing approach for the health of the community.

Commercial Applications from Microbial Filtration in Space

Opening a window for a breath of fresh air is not an option in space, and cleaning agents can become a contaminant themselves. Biological filters that use microbes to remove air pollutants offer a solution; however, they pose risks. Harmful bacteria could grow on the filters and cause damage to equipment and systems on the space station.

> Using the microbial analysis technology developed for ESA, Bioclear can identify the presence of a bacterial threat in water or soil and estimate the power of that threat.

The ISS has been a home to humans for more than 15 years. Keeping the space station air clean and safe can be a challenge since contaminants build up over time. Astronauts on long missions are particularly susceptible to microbial infections due to their weakened immune systems. Bioclear, a Dutch company specializing in soil pollution, teamed with ESA to develop an air filter for the ISS that uses bacteria to convert contaminants into carbon dioxide and water for reuse. The company developed a screening technique

New Filtering Technology "Sweats the Small Stuff"

A partnership between the European Space Agency and Bioclear resulted in a new biological filter and DNA screening technology being commercialized through a spin-off company, Bioclear Microbial Analysis (BMA). BMA reported assets greater than $500,000 and seven employees at the end of 2017. BMA was created to focus on the use of this filtering and screening technology in terrestrial applications, including the identification of microbial influenced corrosion (MIC). The global market price to prevent MIC is $7 billion.

based on DNA analysis to help astronauts check whether harmful bacteria developed on a filter.

Using the microbial analysis technology developed for ESA, Bioclear can identify the presence of a bacterial threat in water or soil and estimate the power of that threat. Bioclear's technology has found use in a variety of commercial applications, from tracking hygiene issues in drinking water to monitoring pollutant-degrading bacteria in contaminated soil. There has been great demand from iron pipeline owners to identify where soil is inhabited by corrosion-causing bacteria so inspectors can target weak spots along the pipeline.

Space-tested Fluid Flow Advances Infectious Disease Diagnoses

A low-energy medical device that can diagnose infectious diseases on-site may soon be operating in remote areas of the world that have limited access to power sources. With a reduced need for energy and on-site diagnosis, less time would be needed between identifying a disease and beginning the treatment for it.

The device that could quickly identify diseases such as HIV/AIDS or tuberculosis relies on a deeper understanding of capillary flow. That deeper understanding is the result of research conducted on the ISS.

Assisted by researchers at NASA's Glenn Research Center in Cleveland, Ohio, Dr. Mark Weislogel of Portland State University in Oregon conducted the Capillary Flow Experiment (CFE)—a suite of fluid physics experiments conducted on the space station.

Capillary flow, also known as wicking, is the ability of a liquid to flow without the assistance of gravity and other external forces. It even works in opposition to those forces. When you stick a straw into a glass of water, the water will rise perhaps a few millimeters in the straw before you begin to drink through it. Or consider how a paper towel will draw, or wick, liquid into it.

By relying on the principles of capillary flow, the device uses much less energy and can provide medical professionals with a valuable tool in areas with limited resources.

A view of Capillary Flow Experiment-2 Interior Corner Flow 3 vessels set up during an experiment aboard the ISS. This study looks at capillary flow in interior corners.

Image credit: NASA

The effect of capillary forces is more dramatic in the absence of gravity. For example, the water would rise and completely fill a straw before you began to drink through it.

CFE was a basic fluid physics investigation that refined our understanding of how capillary action helps fluids flow. The principle has application in many fluid-handling systems—from fuel tanks to cooling systems to medical devices. Cell samples in the form of bodily fluids or blood are placed in medical devices. Enzymes burst the samples, leaving behind DNA or RNA, which is then captured on a bead that is processed by the device to identify the infectious virus. Capillary flow such as that studied by CFE is used to manage and direct the flow of the cell samples inside the device.

David Kelso, Ph.D., of Northwestern University in Evanston, Illinois, developed the simple,

inexpensive device. Kelso and his team were using energy-consuming items such as batteries and motors to operate the device; however, when his designs did not work as expected in the lab, Kelso turned to Weislogel. Kelso explained that he and his team thought that gravity would pull fluids through the device, but Weislogel had the understanding that capillary action would do this based on his previous work in microgravity.

By relying on the principles of capillary flow, the device uses much less energy and can provide medical professionals with a valuable tool in areas with limited resources. The device began field testing in 2015.

Although a primary focus of the CFE research was fluid management in space where gravity is nearly absent, the basic principles of capillary flow can be used on Earth as well. The most direct applications for CFE research are immediate design improvements for most life support equipment aboard spacecraft. In addition, Weislogel believes that terrestrial applications will be commercially viable when applying the unique results of space station research.

Research in the microgravity environment of space continues to impact our lives here on Earth. As with the medical device, this deeper understanding of capillary flow could change how fluid-handling systems are designed and operated in any number of applications.

Improved Oil Exploitation Strategies

The world is steadily transitioning away from the use of fossil fuels. However, with oil still an essential part of global industrial output, the efficient exploitation of oil field resources remains a key element in reducing costs and environmental impacts in the industry. Improving the efficiency of oil recovery is currently a major challenge. At about 4000 m (13,123 ft) below ground level, hydrocarbon fluids are highly sensitive to applied forces—not only gravity, but also temperature and pressure gradients. The prediction of hydrocarbon composition is an important factor that contributes to the choice of reservoir exploitation strategies. Since the cost of extracting resources increases with depth, oil companies are interested in reliable thermodynamic models that will allow the characterization of an entire reservoir using a reduced number of exploratory wells.

One major area of research supported by ESA involves the observation of thermodiffusion in fluids (also known as the Soret effect), and the determination of thermodiffusion (Soret) coefficients. Thermodiffusion plays a crucial role in many naturally occurring processes, ranging from convection in oceans to component segregation in solidifying volcanic lava, and it can seriously affect industrial processes such as the manufacture of semiconductors and oil-in-water emulsions.

...the efficient exploitation of oil field resources remains a key element in reducing costs and environmental impacts in the industry.

In the past 15 years, ESA has supported numerous thermodiffusion experiments that have yielded significant amounts of data. This research included the joint Diffusion and Soret Coefficient (DSC) Measurements and Diffusion Coefficients in Mixtures (DCMIX-1) experiment, which took place on the ISS at the end of 2011. The DSC/DCMIX-1 experiment accurately determined isothermal and thermal diffusion coefficients for different samples that contained systems representing the three main families of crude oil. This has been followed up by subsequent experiments. The basic principle of the experiments is to expose representative liquid mixtures to a temperature gradient in weightlessness where gravity-

Good Vibrations...and Their Effect on Liquid

The Selectable Optical Diagnostics Instrument-Influence of VIbrations on DIffusion of Liquid (SODI-IVIDIL) experiment demonstrated the agreement between experimental and predicted results of the diffusion and thermodiffusion coefficients. These data shed light on the complex mechanisms behind vibration-induced convection, and provided useful insight on how to control fluids in space—techniques that can support new oil exploitation strategies on Earth.

driven convection is avoided. When a stable liquid composition profile is reached, measurements of the variations in density caused by the Soret effect are performed by interferometry.

Successfully generating isothermal and thermal diffusion coefficients for different component mixtures serve as the standard for ground experiments and for numerical modeling of hydrocarbon mixtures. Once the Soret coefficients are determined for different samples, the scientific community will be able to test the predictions of numerical simulations of molecular dynamics and, eventually, model the distribution of components within underground reservoirs.

Materials

The International Space Station (ISS) provides a unique laboratory environment for the testing of new materials. Sedimentation and buoyancy-driven convection do not take place in microgravity, thus allowing us to witness how materials change and develop over longer periods. This allows researchers to manipulate their materials in unique ways. These opportunities are leading to a better understanding of how material processes work on Earth, thereby enabling the manufacturing of new materials with well-defined structures, improved strength and better function.

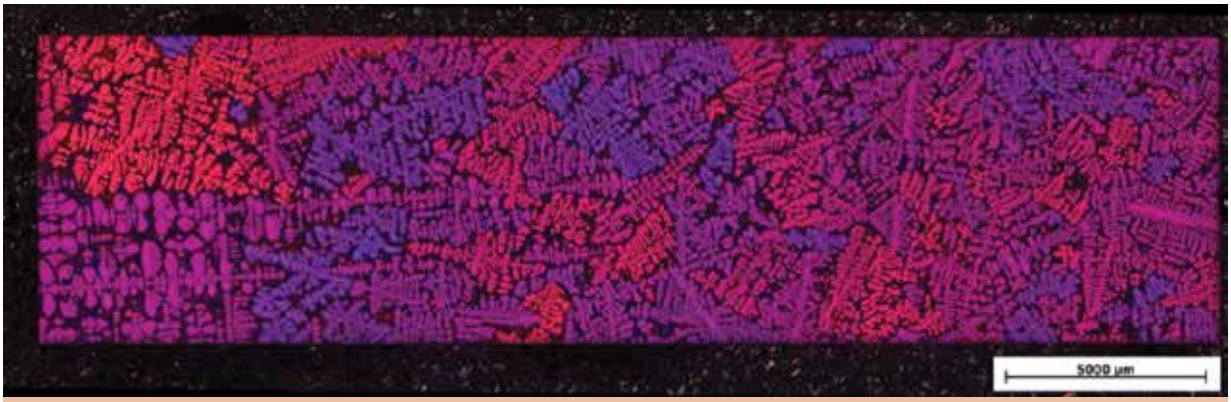
Improved Industrial Casting Models and Casting Processes

The world is facing many ecological and economic challenges, The European Space Agency's (ESA's) materials science research is addressing these challenges as part of a world-class program involving hundreds of international partners from academia and industry. The main goal of this research is to increase understanding of material solidification processes in order to develop new, stronger, lightweight materials that will have a significant impact on industry. Another important goal of the research is to help resolve some of the most pressing issues facing the planet, such as improving fuel efficiency, and improving the consumption and recycling of materials.

Columnar-to-Equiaxed Transition in Solidification Processing (CETSOL) is one of the many materials projects supported by ESA on the ISS. It was the first experiment to start processing in the Materials Science Laboratory on the ISS at the end of 2009.

The main goal of this research is to increase understanding of material solidification processes in order to develop new, stronger, lightweight materials that will have a significant impact on industry.

CETSOL has been studying the microstructure of aluminum alloy samples formed during solidification, specifically focusing on how columnar dendritic or tree-like structures in a solidifying melt evolve into randomly oriented "branches," the 'equiaxed' structure, and the parameters that influence this transition. The determination of the internal (micro)



A typical microstructure obtained in a CETSOL sample containing a grain refiner. The sample was directionally solidified in the ISS Materials Science Laboratory.

Image credit: CETSOL science team

structure in processed metal samples is of great importance in these experiments, as the microstructure influences an alloy's characteristic properties such as strength, toughness, and resistance to fatigue and (high-temperature) creep. The existence of these non-uniform dendritic forms in an alloy microstructure implies that the mechanical properties of the alloy can vary considerably throughout the sample. This non-uniformity makes matching the specific casting of an alloy with the appropriate application much more complex, especially in high-end industry.

These experiments help to validate and/or improve industrial casting models with vital benchmark data from space where gravity-induced convection does not mask certain physical phenomena that occur in molten liquids—phenomena such as multiphase fluid flow, diffusion, capillarity effects and heat transport that affect the properties of materials. The software company Transvalor has used the results of analysis from the CETSOL experiment to improve their own commercial software code THERCAST®. This code is used by a variety of users to improve their casting products. The casting industry, especially for high-end industry such as aerospace, is relying more heavily on the benefits of using numerical models to determine casting methods and conditions needed in anticipation of producing materials with specific performance characteristics that are tailored to particular applications.

ESA astronaut Alexander Gerst is wearing SpaceTex experiment fabrics while on the ISS exercise bike during ESA's Blue Dot mission in 2014.

Image credit: ESA and NASA

Clothes "Made In Space"

Sweat is an unwanted exercise companion. Space-proven garments are inspiring innovative textiles for the gym and for those working in extreme conditions on Earth.

A warm and humid environment is an ideal scenario for bacterial, viral and fungal super-infections. Space garments offer physical comfort by acting like a second skin, are more hygienic and allow freedom of movement. The SpaceTex experiment assessed new fabrics to improve heat transfer and sweat management during exercise. The fabrics were chosen for their antibacterial properties. T-shirts with ultrashort drying times would be very useful to athletes, as well as firefighters, mine workers and members of the armed forces. This is the first clothing physiology experiment performed in microgravity. Sportswear manufacturers are hoping to improve their products. A modified polyester has already been created for the Swiss military.

Space-proven garments are inspiring innovative textiles for the gym and for those working in extreme conditions on Earth.

The lack of convection in space affects the way body heat and sweat are transported and absorbed into an astronaut's clothing. Astronauts often report sweating more during exercise in orbit compared to exercise on Earth. Heat envelops their bodies like an aura. High-performance fibers were assessed on the space station for how comfortable the clothes were in comparison to conventional cotton garments. Positive feedback coupled with the data from the experiment are helping optimize astronaut clothing for future long-term missions such as a future journey to Mars.

Textiles would have to be specially adapted for use in space—new fabrics with better thermal and sweat management need to maintain the astronauts' cooling mechanism and reduce microbiological contamination on the spacecraft.

Sleepwear with a Purpose

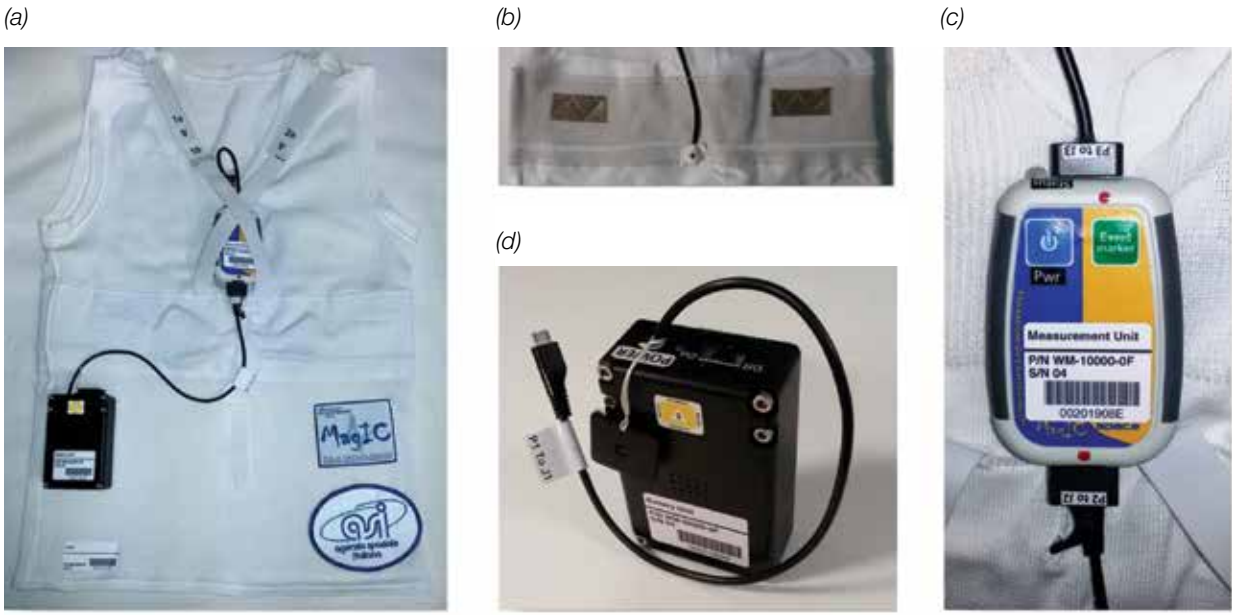
Traveling in space represents a dream come true for astronauts; however, these crew members do not always have sweet dreams while there. In fact, astronauts experience poor sleep quality. An investigation aboard the ISS looked for the reasons why.

Wearable Monitoring—an investigation that is part of the Italian Space Agency (ASI) Futura Mission—used a smart garment to unobtrusively collect data on sleep physiology during spaceflight.

Based on research that was conducted on Earth, researchers suspect that abnormal activation of the autonomic nervous system might interfere with sleep during spaceflight. The investigation looked at the effects of microgravity on cardiac mechanics during sleep and how these mechanics are related to autonomic activity, which can be identified by analyzing specific patterns in the heart rate.

Adequate, quality sleep is important for overall health and physical and cognitive performance for astronauts and people on Earth.

Current methods of measuring these patterns require waking the subject. However, ESA astronaut Samantha Cristoforetti demonstrated that the garment did not interfere with sleep by wearing it for seven in-flight sleep recordings taken over several months. The lightweight, cotton vest is embedded with sensors made of textile silver-coated fibers—a technology called MagIC-Space. The sensors monitored traditional vital signs—i.e., electrocardiograms (ECG), respiration,



The MagIC-Space system. (a) the vest with its components; (b) the inner part of the vest with the ECG textile electrodes, the textile respiratory sensor and the thermometric probe for measuring skin temperature; (c) the electronic module, including the sensor for the assessment of the seismocardiogram; (d) the battery box for the power supply.

Image credit: Marco Di Rienzo, Fondazione Don Carlo Gnocchi, Milano, Italy

body accelerations and skin temperature—and, for the first time, cardiac mechanics such as contraction and relaxation times.

"The beating heart produces vibrations in the thorax, and the vest measures and analyzes these minute vibrations, signals known as a seismocardiogram," explained principal investigator Marco Di Rienzo of Italy's Fondazione Don Carlo Gnocchi. "Commonly, cardiac contractility is evaluated by ultrasound. This produces a detailed picture of heart performance, but only allows measurement during limited times in a controlled environment and requires an expert operator. The seismocardiogram measured by the wearable device provides a prolonged beat-to-beat profile of cardiac mechanics in an unobtrusive manner, out of a laboratory setting."

Researchers can use these data on sleep physiology in microgravity to explore causes of astronauts' poor sleep quality. The vest also could be used as a non-invasive and less disruptive way to continuously monitor astronauts for a wide range of vital signs during sleep and waking hours.

On Earth, a version of MagIC-Space technology could simplify the study and treatment of sleep disorders. About a quarter of people in developed nations suffer from sleep disorders, and studying them currently requires complex, specialized instruments that can be expensive and time-consuming to operate. The vest could simultaneously and unobtrusively monitor autonomic, electrical and mechanical heart activity and respiration. Additionally, as part of a smart garment, the technology can provide real- time fitness tracking by measuring complex cardiac and respiratory function at a more detailed level than many smart garments available in today's market place.

Adequate, quality sleep is important for overall health and physical and cognitive performance for astronauts and people on Earth. This investigation could mean sweeter dreams for everyone.

FUTURA, ASI's second long-term mission, included nine scientific research and Italian technology projects performed during the 6 months that Cristoforetti spent aboard the space station.

Sleep Monitoring Receives a Valuable "Wake-up Call"

Wearable Monitoring confirmed the use of a smart garment to monitor a wide range of vital signs during sleep in microgravity. This resulted in less- complicated devices used to measure sleep patterns on Earth, as well as the prospect of doctors monitoring patients located in remote locations.

Three-dimensional Bioprinting in Space

Nanotechnology development allows for the management of living cells, tissue spheroids and synthetic microscaffolds by using magnetic fields. This, in turn, leads to attempts to create magnetic bioprinters.

However, the first attempts to create magnetic bioprinters showed that terrestrial gravitation represents a significant limitation. It is reasonable to assume that in a gravity-free environment, magnetic and diamagnetic levitation will allow not only so-called "formative" biofabrication of three-dimensional (3-D) tissue constructions, but even programmable self-assembly of 3-D tissue constructions in a controlled magnetic field. The space magnetic 3-D bioprinter, which can manage tissue spheroids in microgravity, is a practical implementation of the new perspective concept of formative biofabrication. Microgravity biofabrication on the basis of magnetic forces transforms the technology of 3-D bioprinting and opens real opportunities for programmable self-assembly of tissue and organ constructions of tissue spheroids in 3-D space without solid scaffolds. Formative fabrication and programmable self-assembly are revolutionary manufacturing and biofabrication technologies of the 21st century.

The space magnetic 3-D bioprinter, which can manage tissue spheroids in microgravity, is a practical implementation of the new perspective concept of formative biofabrication.

Today, there are three main 3-D bioprinting technologies: extrusion, inkjet and laser-based bioprinting. These methods have common limitations such as slow speed and the inability to create 3-D constructs with complex geometry. Therefore, new approaches such as acoustic or magnetic bioprinting using patterned physical fields for predictable cells spreading will evolve.

The main idea is to use microgravity as a co-factor of bioprinting technology. This concept means using a scaffold-free, nozzle-free and label-free (i.e., without using magnetic nanoparticles) approach called formative biofabrication, which has the edge over classical bottom-up additive manufacturing. This technology could be commonly used for space radiation studies to provide long-term crewed space flights, including the moon and Mars programs.

3D Bioprinting Solutions developed a novel space 3-D bioprinter (see image below), which will enable rapid, label-free 3-D biofabrication of 3-D tissue and organ constructs in the condition of microgravity by using magnetic fields. Meanwhile, a sophisticated holistic cuvette system for delivering living objects to the ISS, performing biofabrication, and transferring bioprinted constructs back to Earth has been developed.

Rapid biofabrication of 3-D organ constructs of thyroid gland and cartilage using tissue spheroids (i.e., thyreospheres and chondrospheres) in the conditions of natural space microgravity will be launched during space experiments. After the return

3-D model of magnetic bioprinter (Organ.Aut).

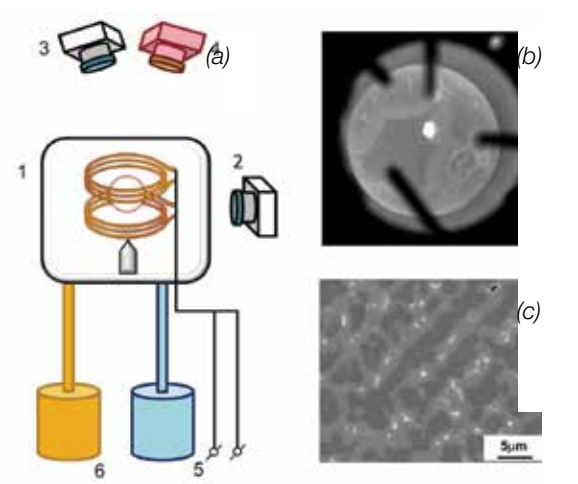
Image credit: Private Institution Laboratory for Biotechnological Research "3D Bioprinting Solutions", Moscow, Russia

of bioprinted constructs to Earth, histological tests will be conducted to examine the internal structure.

The 3-D bioprinter will become a part of ISS scientific equipment for conducting further international experiments by any scientific groups and companies interested in 3-D bioprinting technology. That means we are developing a novel shared research infrastructure for unique biomedical research on the ISS.

International Space Experiments: PARSEC and MULTIPHAS

Invention of modern materials for different applications is based on complex fundamental studies. New properties of materials are often formed under the strongly nonequilibrium conditions of heat treatment where the heating and cooling rates are high. In the space experiments PERITECTICA (international acronym PARSEC) and KINETICA (acronym MULTIPHAS), the metal melts are tested with the cooling rate up to 30°C (86°F) per second. MSL-EML, a unique electromagnetic levitation furnace developed by ESA, is used for this purpose.



(a) Sketch of the electromagnetic levitator furnace MSL-EML: 1 – processing chamber; 2,3 – high-speed camera; 4 – pyrometer; 5 – power supply block; 6 – block of water cooling. (b) View of the sample levitating in the alternating magnetic field of high frequency. (c) Microstructure of the processed Nd2Fe14B1 sample.

Image credit: ESA

The new technology allows for the production of coatings with reduced friction coefficient, as well as high corrosion resistance, strength and wear capacity.

The experimental data on a wide class of materials, including magnetic, constructive and amorphous alloys, provided important information for practical applications. Using the data obtained onboard the ISS, a range of functional coatings with various properties has been identified. The new technology allows for the production of coatings with reduced friction coefficient, as well as high corrosion resistance, strength and wear capacity. Therefore, this research has led to the successful development of materials that can efficiently serve humans in space and on Earth.

Levitating and Melting Materials using Coulomb Force Without a Container

On Earth, a liquid needs a container to stay put. Because no containers are suitable for temperatures higher than 2000°C (3632°F), it is difficult to melt materials that have a high melting point. Containers react to high temperature and contaminate the materials.

In microgravity, liquid can be levitated easily and does not need containers. This method of handling materials without a container is called “containerless processing.” This processing allows us to closely investigate the behavior of materials in their molten state, which is difficult to do on Earth. The electrostatic levitation method, which is one containerless processing technique, uses the Coulomb force between charged samples and electrodes, and controls the sample position by using high-speed feedback from the camera image.

In microgravity, liquid can be levitated easily and does not need containers.

The Japan Aerospace Exploration Agency (JAXA) has been developing this technique on Earth for more than 20 years. In 2015, JAXA completed the development of the Electrostatic Levitation Furnace (ELF) for the ISS. The ELF is a facility for material science that melts levitating materials having a very high melting point, measures their properties, and solidifies them from a supercooled state by taking advantage of the microgravity environment. The main target sample of the ISS mission is oxides. The melt oxides cannot be levitated by electromagnetic force, and it is difficult to do so by electrostatic levitator on the ground because the electric charge of nonconductors is much less than that of conductors.

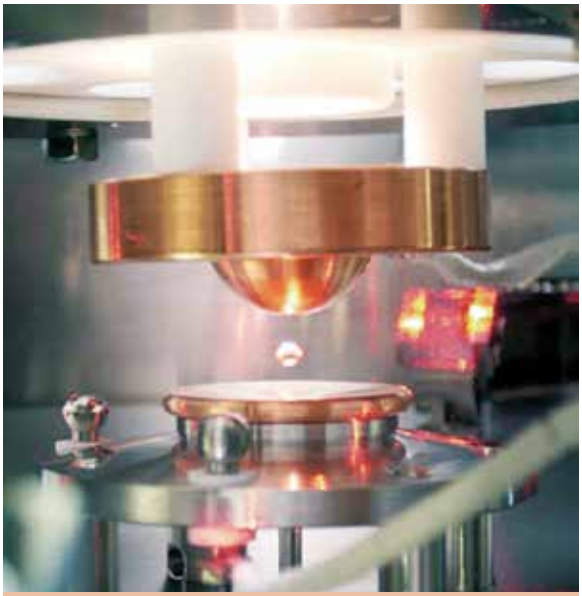
The techniques of measuring the thermophysical properties of high-temperature melts were improved with a ground-based facility during the preparatory research for the ELF on Kibo. Many thermophysical properties of refractory metals have been revealed for the first time. Moreover, containerless processing can provide a large, supercooled state that allows for the formation of different crystalline structures and phases from which new materials can be created.

We levitated and melted barium titanate (BaTiO3) without a crucible during a ground-based experiment, and crystallized it through supercooling. As a result, we succeeded in developing a high-performance material that has a huge dielectric constant and is unaffected by temperature changes.

In 2018, the initial checkout of the ELF was completed onboard Kibo, which included the density measurement of molten alumina, and the ELF experiment finally began. ISS-ELF can measure the thermophysical properties (i.e., density, surface tension and viscosity) of high-temperature melts above 2000°C (3632°F). (Tamaru, H. et al., 2018, **https://doi.org/10.1007/s12217-018-9631-8**).

The thermophysical properties data of materials at a high temperature is useful for the study of liquid states and the improvement of numerical simulation by modeling the manufacturing processes using the liquid state as the basic data for computer-based casting technology to be applied to efficient turbines for electric generation systems, aircraft, and the next generation of jet engines. Moreover, the interfacial energy of immiscible melts will be measured by creating a core-shell droplet configuration, which otherwise cannot be obtained on the ground due to sedimentation.

The ELF technology will dramatically improve the quality of the fundamental data of material science by the thermophysical data acquired onboard Kibo. We also expect to find unknown characteristics of materials through crystallization using containerless processing.



The ground-based electrostatic levitator. Controlling the sample position using Coulomb force between charged samples and electrodes.

Image credit: JAXA

Molten alumina levitating in the center of six electrodes onboard the ISS.

Image credit: JAXA

Transportation Technology

Combustion science is one of the longest-running fields of research on the International Space Station (ISS). There is a long-running campaign to understand just how both simple and more-complex fuels burn in space. Understanding this process in microgravity helps to refine combustion models on Earth where gravity and turbulent buoyancy-driven convection flows make this process too difficult to model. Recent observations on the ISS have shown that a phenomenon known as "cool flames" can be witnessed in the combustion chambers in orbit to understand how lower temperature burning could have significant applications toward more efficient fuel use and new combustion engine designs in the future. Vehicle docking technology used for the ISS is finding applications in fields where advanced sensors and robotics are used for safety improvements.

Automating a Better Rendezvous in Space

Safe, reliable and affordable commercial access for research aboard the ISS is a critical component of the ISS Partnership. Partnerships with cargo transportation services make this access possible, and other partnerships continue to provide technological advances to improve it.

One such advance, Triangulation & Light Detection and Ranging Automated Rendezvous & Docking (TriDAR), is an automated rendezvous and docking sensor with a long-range Light Detection and Ranging (LiDAR) system. LiDAR uses a pulsed laser beam to measure variable distances to an object, combining this with other data to generate precise, three-dimensional (3-D) information about the shape and surface characteristics of the object.

TriDAR can collect 3-D images up to 5 km (3.1 m) and can be applied over a wide range of applications including rendezvous and docking, mapping, navigation and hazard avoidance. Using a patented optical design, TriDAR can collect data anywhere within a 60-degree by 45-degree field of view. Created by Neptec Design Group/ MacDonald Dettwiler and Associates (https://neptec.com/), TriDAR was specifically designed for missions that require high levels of autonomy, such as planetary rovers and satellite servicing. The hardware and algorithms provide maximum operational flexibility, thereby allowing the sensor to adapt to rendezvous and docking with different targets and approach profiles, even after launch. TriDAR uses a laser-based 3-D sensor and, optionally, a thermal imager to collect 3-D data of its target. Software compares the image to the known shape of a target spacecraft and calculates relative range, rates, and position between the spacecraft and docking station.

This technology, tested on three Space Shuttle missions, now serves as a rendezvous and docking sensor for Orbital ATK's (now Northrop Grumman Innovation Systems) Cygnus spacecraft cargo resupply missions to the space station. An optional thermal imager provides extended range tracking and short-range guidance, and multiple hardware configurations support different mission types. The automated system allows Cygnus to approach the ISS and position itself for capture by the space station's robotic arm. TriDAR guides the final rendezvous phase, from a maximum range of approximately 1 km to final capture location at about 10 meters (32 ft). Space station crew members then grapple the vehicle with the space station's robotic arm and connect it to an ISS node port.

Neptec Design Group, Ltd., a Canadian spaceflight engineering company founded in 1990, develops intelligent spaceflight sensors, payloads, instruments and equipment for the space market, and has been a NASA and Canadian Space Agency (CSA) prime contractor since 1995. Founded in 2011, Neptec Design Group focuses on migration of these technologies to terrestrial markets and is a leading manufacturer of real-time 3-D LiDAR scanners for robotics and autonomous systems.

Safe, reliable and affordable commercial access for research aboard the ISS is a critical component of NASA's mission.

Three-dimensional Technology Offers Clarity in the "Foggiest" of Situations

Neptec Design Group Ltd., now part of MacDonald Dettwiler and Associates, honed expertise in Triangulation & Light Detection and Ranging Automated Rendezvous & Docking—i.e., TriDAR—technologies in development of autonomous spacecraft docking sensors and algorithms for the Space Shuttle, International Space Station, and Orbital ATK (now Northrop Grumman Innovation Systems) Cygnus resupply spacecraft. Neptec Design Group is estimated to employ around 100 people, and has an annual revenue of $10 million. In 2011, a spin-off corporation, Neptec Technologies Corp., was created to translate technologies such as Light Detection and Ranging (LiDAR) for terrestrial applications. Neptec Technologies employs from 11 to 50 employees, with an annual revenue of up to $10 million. The corporation currently offers the OPAL-360 (Obscurant-Penetrating Auto synchronous LiDAR) device—a three-dimensional (3-D) scanner that can work in real time and see through obscurants such as dust, snow or fog. The device has found traction in industries such as mining, rail, aeronautics and marine transportation. In 2018, Rolls Royce debuted a sophisticated new "situational awareness system" for marine vessels using Neptec LiDAR technologies to create a 3-D map of the surrounding area for navigation purposes.

Cool Flame Research Aboard the Space Station may Lead to a Cleaner Environment on Earth

The anxious moments of trying to make the next service station, one eye on the fuel gauge, low-fuel light aglow, may become less frequent in the future. Even choosing which fuel is better for the environment may be easier, thanks to droplet combustion research on the ISS. Better mileage and a very real possibility of reduced pollution on Earth may be possible in the future.

Researchers from academia working with NASA's Glenn Research Center in Cleveland, Ohio, conducted the Flame Extinguishing Experiments (FLEX and FLEX 2), which revealed new insights into how fuel burns.

Led by principal investigator Forman Williams of the University of California, San Diego, who has studied combustion for more than 50 years, and co-principal investigator Vedha Nayagam of Case Western Reserve University, Cleveland, Ohio, the FLEX investigations revealed a never-before-seen, two-stage burning event. Although a heptane droplet of fuel appeared to extinguish, it actually continued to burn without a visible flame. This knowledge could contribute to reduced pollution and better mileage in engine design because of improved prediction of flame behavior during combustion.

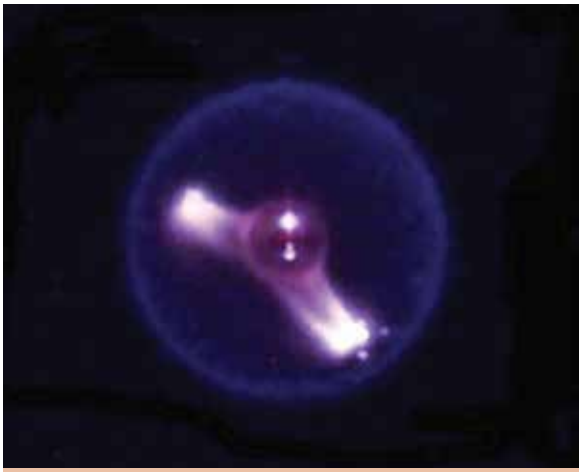
After decades of flame studies that have produced well-understood, theoretical models and numerical simulations, the FLEX flame investigations in microgravity produced this unexpected result. This is the first time scientists have observed large droplets (i.e., approximately 3 millimeters) of heptane fuel that had dual modes of combustion and extinction. The fire went out twice—once with and once without a visible flame. Although the initial burn had a traditional hot flame, the second-stage vaporization was sustained by what is known as cool flame, chemical heat release.

A cool flame is one that burns at about 600°C (1,112°F). To understand how cool this is, consider that a typical candle is about two-and-a-half times hotter, burning at around 1,400°C (2,552°F).

The phenomenon of the continued burning of heptane droplets after flame extinction in certain conditions was not anticipated when the study was designed.

This result came during the FLEX investigation on the space station using the Multi-User Droplet Combustion Apparatus in the Combustion Integrated Rack (CIR).

The FLEX investigation in the reduced gravity environment of the space station provides new insight into the mysteries of flames and fuel.



A burning heptane droplet during the FLEX and FLEX investigation on the ISS.

Image credit: NASA

More recent FLEX experiments reveal similar two-stage burning phenomena with n-octane and decane fuels.

While burning the heptane droplets in the CIR, the first stage had a visible flame that eventually went out. Once the visible flame disappeared, the heptane droplet continued rapid quasi-steady vaporization without any visible flame. This ended abruptly at a point called second-stage extinction. At this point, a smaller droplet was left behind. The droplet either experienced normal, time-dependent evaporation or sometimes grew slightly through condensation of vapor in the cloud that formed upon extinction.

The new findings have been published and are available online in Combustion and Flame, the journal of the Combustion Institute. This new discovery will help scientists and engineers modify numerical models and better predict the behavior of flames, fuel and combustion. It also has many long-term implications both in space and on Earth. These findings can help with development of new technology to reduce pollution and increase gas mileage in internal combustion engines. Cool flame burning could also be used to partially oxidize the fuel for use in burners with reduced emissions and better control.

The Homogeneous Charge Compression Ignition engine can replace spark ignition and can be used in any diesel engine, either stationary or for transportation. By merging these two technologies, engines could have the efficiency of burning diesel, while also providing reduced particulate and nitrogen oxide emissions. This could eliminate the need to burn diesel-fuel sprays, which are notorious for pollutant production, according to the researchers.

The FLEX investigation in the reduced gravity environment of the space station provides new insight into the mysteries of flames and fuel. Whether a candle, campfire or some other fuel source, the combustion process may be waiting for the right investigation to illuminate more secrets. Microgravity research may prove to be the tool that helps shine that light.

Space Station Technology Demonstration Could Boost a New Era of Satellite Servicing

The Robotic Refueling Mission (RRM) was built to demonstrate much more than the clever ways space robots can refuel satellites. RRM also demonstrated how space robots can replenish cryogen, a type of coolant, in the instruments of legacy satellites—existing, orbiting spacecraft not originally designed to be serviced.

Delivery to Space Station and Installation

The RRM project included five specialized tools that the Canadian dexterous robot Dextre used to perform several complex servicing tasks, including cutting lock wires, removing caps, opening valves, and replacing electrical connectors. All these precision motion tasks were controlled by operators 322 km (200 miles) below in Houston while the crew slept or performed other important tasks.

New hardware deliveries to the space station helped outfit the RRM module for a new set of operations. Dextre added two new task boards to the RRM that included additional satellite cryogenic and electrical

RRM helps to usher in an era of serviceable spacecraft that breaks the paradigm of “one and done,” thereby making spaceflight more sustainable, affordable and resilient.

interfaces, and four new tool adapters for the RRM Multi-Function Tool. These task boards launched a new Dextre tool—the Visual Inspection Poseable Invertebrate Robot (VIPIR)—a snake-like inspection tool that was built by the Satellite Servicing Projects Division (SSPD) at NASA's Goddard Space Flight Center. The VIPIR was used to peer inside plumbing lines or under thermal blankets. The RRM On-Orbit Transfer Cage (ROTC), was also brought up to secure the new hardware components in the Japanese airlock so that Dextre could grab the components once they were transferred outside the space station.

Astronauts mounted the ROTC on the airlock table within the Japanese Experiment Module, and then installed the task board and VIPIR onto the ROTC.

When the airlock was opened, the slide table extended outside the space station, giving Dextre an easy platform from which to retrieve and subsequently install the new hardware.

With the help of the twin-armed Dextre robot, the additional RRM task boards and the RRM tools, the RRM team worked its way through intermediate steps leading up to cryogen replenishment. The RRM and Dextre duo retrofitted valves with new hardware, peered into dark recesses with the aid of VIPIR, replaced electrical connectors and created a pressure-tight vent-line seal. The RRM and Dextre stopped short of actual cryogen transfer for this round of tasks.

RRM Phase 2 was completed in 2015.

The RRM investigation (center, on platform) uses Canadarm2, the ISS robotic arm, and the Canadian Dextre robot (right) to demonstrate satellite-servicing tasks.

Image credit: NASA

Expanding Capabilities and Fleet Flexibility in Space

Cryogenic fluids are used on the ground and in space to make sensitive cameras work better. However, in time, this extremely cold substance turns to gas and slowly vents away, along with camera detector performance. According to Hsiao Smith, technical deputy project manager of SSPD, robotically replenishing these reserves would allow spacecraft instruments to last beyond their expiration date and ultimately permit satellites to perform longer with renewed accuracy.

Smith explains that both the government sector and commercial sector are focused on expanding options. Satellite operators can choose to extend the life of an aging observatory or spacecraft using a future cryogen-toting space tanker instead of retiring or launching a new, costly one. The RRM demonstrations are an important step to eventually enabling that capability.

Preparing for a Servicing-Enabled Future

Since its 2011 launch to the space station on the last space shuttle mission, RRM has demonstrated several important robotic satellite-servicing activities in orbit. RRM used the space station as a test bed for technology research and development in a joint effort with CSA. RRM was removed in 2017 and disposed of on SpaceX-10.

The next phase, RRM3, is scheduled to launch in November 2018, and will test the actual transfer of cryogens in orbit. RRM3 continues to advance satellite servicing, and also helps enable travel to destinations such as the moon and Mars, since cryogen can also serve as a potent propellant necessary for deep space exploration.

NASA developed RRM to demonstrate how remotely operated robot mechanics could extend the lives of the hundreds of satellites in space. Costly assets traveling above Earth in low-Earth orbit and geosynchronous Earth orbit, satellites deliver essential services such as weather reports, cell phone communications, television broadcasts, government communications and air traffic management. Servicing capabilities greatly expand the options for government and commercial fleet operators in the future, and could potentially deliver significant savings in spacecraft replacement and launch costs to satellite owners.

NASA continues to test capabilities for a new robotic servicing frontier, with a RRM3 in the works. In conjunction with RRM, the SSPD team has been studying a conceptual servicing mission while building the necessary technologies, including an autonomous rendezvous and capture system, a propellant transfer system and specialized algorithms to orchestrate and synchronize satellite-servicing operations.

RRM helps to usher in an era of serviceable spacecraft that breaks the paradigm of “one and done,” thereby making spaceflight more sustainable, affordable and resilient.

Robotics

The ability of robots to work alongside the human crew to perform necessary tasks more efficiently is key to enhancing human spaceflight missions. These tasks include those that are monotonous or risky and impose on the available time astronauts have to focus on science experiments. The International Space Station (ISS) provides an excellent platform where these operational concepts and procedures can be developed, tested and evolved in an actual space environment while demonstrating robotic systems' performance and reliability over the long duration. The precision and reliability requirements for space robotics led to dual-purpose technologies and advanced robotic capabilities for use on Earth.

Robonaut's Potential Shines in Multiple Space, Medical and Industrial Applications

When scientists and engineers began developing a humanoid robot for space exploration, they set out to create robotic capabilities for space exploration; however, they did not limit their design for use in microgravity. They decided to also lend a robotic hand, along with many other appendages and abilities, to those in need on Earth.

The first Robonaut was a collaborative effort between NASA and the Defense Advanced Research Projects Agency. It was built for space exploration missions such as performing skilled hand movements during extravehicular activity (EVA)—or spacewalks. However, NASA gained significant expertise in expanding robotic technologies for space and Earth applications through successful creation of partnerships with outside organizations.

The latest iteration of Robonaut—Robonaut 2 (R2)—was co-developed with General Motors (GM) through a Space Act Agreement. R2 is a more dexterous robot, built for the microgravity environment to utilize human-rated tools, assist with ISS activities and safely work side-by-side with astronauts. Although R2 resides onboard the space station, many of the technologies developed for Robonaut are being adapted for use on Earth. Here are three examples:

NASA continues to look for new collaborative opportunities to leverage resources that will help all partners increase their chances of making better products...

RoboGlove Technology

A robotic glove, called RoboGlove, was developed as a grasp assist device after NASA and GM recognized overlap between what astronauts needed in space and what factory workers could use on the ground. RoboGlove can augment human tendons to help both astronauts and factory workers with grasping tasks and potentially minimize the risk of repetitive stress injuries.

Since astronauts wear pressurized spacesuit gloves during a spacewalk, they exert more force to hold a tool or tighten a screw, which causes fatigue. RoboGlove could help astronauts close their gloves, thereby reducing the amount of effort they apply while conducting EVA tasks, in much the way power steering helps to steer a car.

At GM, factory workers on assembly lines perform tasks that involve gripping tools repeatedly throughout their work day. They tire more quickly due to either exerting a high amount of force at multiple intervals or exerting force for long periods of time. RoboGlove may help factory workers grip a tool longer with less discomfort by reducing the amount of force needed. This could result in less fatigue and fewer stress injuries.

NASA and GM have licensed the patented RoboGlove technology to BioServo (**http://www.bioservo.com/**) to produce a commercial version. GM plans to use the glove technology in future advanced vehicle safety systems and manufacturing plant applications. NASA is experimenting with the technology in its Earth laboratory and integrating it into a working spacesuit glove for possible future use by crew members.

The Robo-Glove was built through the continuing partnership between NASA and General Motors. It uses R2 technology to decrease fatigue and stress when a human grasps an object.

Image credit: NASA

The RoboGlove also generated interest from the medical community. For instance, patients in rehabilitation may benefit from a device that helps them recover their ability to grasp objects. An adapted glove that is able to both open and close could help patients who are recovering from brain injury. NASA engineers have explored ways to adapt the glove for people with partial hand amputations, as well. A future partnership with a medical center or research institution could expand RoboGlove technology to medical settings, in addition to its use for space exploration and factory work at GM.

Exoskeleton Technology

NASA and The Florida Institute for Human and Machine Cognition (IHMC) (**https://www.ihmc.us/**), with the help of engineers from Oceaneering Space Systems (**https://www.oceaneering.com/space-systems/**) of Houston, jointly developed a robotic exoskeleton called X1. The X1 technology, derived from Robonaut, may someday help astronauts stay healthier in space as well as assist people with physical disabilities on Earth.

Currently in the research and development phase, X1 is a 57-pound robotic device designed to be worn over the human body either to assist or inhibit movement in leg joints. Worn over the legs with a harness that extends up the back and around the shoulders, X1 has 10 degrees of freedom, or joints: four motorized joints at the hips and knees, and six passive joints that allow for sidestepping, turning and pointing, and flexing a foot.

Employing IHMC's experience in exoskeleton development for paraplegics, NASA and IHMC made R2 arm technology slim enough to allow a person in a wheelchair to use it to get out of the wheelchair. The X1 device has the potential to produce enough force to provide assisted walking over varied terrain to paraplegics or other patients in rehabilitation settings.

In addition to the IHMC and NASA applications of the X1 technology, researchers at the University of Houston (**http://www.uh.edu/**) are adapting an exoskeleton that will be controlled by brain signals. This type of exoskeleton would use a device that is attached to a person's head to read signals that the brain sends to the legs to get them to move.

Telemedicine Applications

The Houston Methodist Research Institute (**http://www.houstonmethodist.org/research/**) and NASA worked together to adapt Robonaut technology for use in telemedicine (i.e., conducting medical procedures through electronic communication) by tasking R2 to perform an ultrasound scan of a medical mannequin and use a syringe as part of a procedure.

With human control of the teleoperated R2, tasks were performed with accuracy and efficiency using R2's dexterity to apply the appropriate level of force and its vision system to monitor progress. This demonstration of R2's capabilities could potentially allow physicians to conduct complex medical procedures on humans in remote locations on Earth or in space.

NASA's Space Technology Program is developing, testing and applying robotic technologies through these kinds of innovative partnerships. NASA continues to look for new collaborative opportunities to leverage resources that will help all partners increase their

chances of making better products, as demonstrated by the numerous current applications of R2 technology. Use of the space station as a test bed for such robotic and future technologies will be vital to human exploration and beneficial to human health.

NASA Project Engineer Shelley Rea demonstrates the X1 Robotic Exoskeleton, which could improve the mobility and strength of astronauts and paraplegics.

Image credit: NASA

Imaging Technologies

Imaging plays an important role in many areas, whether you are on or off the planet. The International Space Station (ISS) provides a platform to test myriad imaging technologies. One such technology is three-dimensional (3-D) imaging that can be used in biomedical, geoscience, surveillance and many other areas.

Space in 3-D

Humans have two eyes to perceive depth and see the world in three dimensions. Back in 2001, the European Space Agency (ESA) started to develop a 3-D camera to navigate a rover on another planet. The power of stereoscopic vision not only opened a new window to space, but also to a whole new range of stereo cameras for business on Earth.

3-D films enhance the illusion of depth perception, thus bringing a feeling of realism to the audience.

ESA astronaut Paolo Nespoli films scientific experiments with the ERB-2 camera onboard the ISS.
Image credit: NASA

3-D films enhance the illusion of depth perception, thus bringing a feeling of realism to the audience. The extra dimension offered by this technology sparked a wish to report on life and work on the ISS in 3-D.

ESA counted on European industry to build a 3-D space camera. Two small European companies miniaturized the electronics and developed software based on their digital image expertise from microgravity research rockets to deliver the Erasmus Recording Binoculars (ERB-1 and ERB-2) for ESA. The camera was not much larger than a shoebox, and contained high-definition optics and advanced electronics. It produced live-streaming 3-D images for the first time in the history of space travel. This occurred in 2011, and showed the space station like never before.

The design and development of ERB were the catalyst for the spin-off company 3D-ONE, which now produces low-cost but high-end 3-D cameras that are sold worldwide. The spin-off company customizes the cameras to meet the specific needs of its customers in areas as diverse as forensics, medicine, surveillance and quality monitoring. By adding hyperspectral capability gleaned from space to a camera, the possibilities multiply—its fine resolution and wide range of wavelengths have applications in agriculture, biomedicine, geosciences and surveillance.

Computing

Whether in space or on Earth, computers are essential in most everyday tasks. Being able to use this technology in a more efficient way is beneficial to most parts of society. The investigations onboard the International Space Station (ISS) produce many data sets that benefit from programs that provide artificial intelligence to evaluate the data and faster processing to reach conclusions in a timely manner. These advancements in computing are useful on Earth in police work, ship tracking, crisis training simulators and scientific discoveries.

New Ways to Analyze and Use Images from Space

Many things become clearer when seen from above, and Earth is no exception. Images of Earth from space provide information that cannot be obtained any other way, and these images continue to make important contributions to science and commerce.

A completed investigation Hyperspectral Imager for the Coastal Ocean (HICO) used a special light-separating camera aboard the International Space Station (ISS) to observe an area of particular interest: the world's coasts.

The space station's unique orbit offers views that differ from those of traditional Earth-viewing satellites. HICO in particular gave scientists exceptional views of the coastal ocean and Great Lakes, thereby providing a tool for managing these critical resources. They used it to estimate chlorophyll-a concentrations (i.e., an indicator of both healthy and harmful phytoplankton), identify Harmful Algal Blooms (HABs) in drinking water reservoirs, and assess water quality. These data also contributed to planning and executing humanitarian relief operations and military actions, and identifying oil spilled from ruptured pipelines.

HICO also created some unique challenges—in particular, processing the sheer volume of data.

> Images of Earth from space provide information that cannot be obtained any other way, and these images continue to make important contributions to science and commerce.

Typical analyses used for land-only and water-only images fell short in coastal zones; therefore, scientists had to develop improved algorithms. An ever-expanding diversity and availability of remote sensing data—from the space station, small satellite constellations, and even drone technology—provide vast, complex data sets, and also drive a need for data processing advances. Although previously, only experts in the field performed capture and analysis of Earth images from space, big data has made its way into the hands of the larger community. Making this wealth of information useful requires rapid innovation in computing technology. These challenges, however, also represent a business opportunity.

"Before, only those of us with the right computers and the right tools could process the data," said HICO Project Scientist Curtiss Davis, now retired from Oregon State University. "We needed a way to readily provide the results—to make HICO data much more widely used and to keep up with the vast amount of spectral info we can now collect."

HySpeed Computing (**http://www.hyspeedcomputing.com/**) responded to these challenges by launching an online web application, The Hyperspectral Imager for the Coastal Ocean Image Processing System (HICO IPS) provides cloud-based remote sensing data analysis. Developed in part through ISS National Lab funding and support, HICO IPS efficiently delivers the power of image analysis to a global user community.

HySpeed Computing President James Goodman called it "the democratization of low Earth orbit," providing wider access to a volume and variety of data.

A prototype commercial product, HICO IPS represents a next-generation image processing application to tackle big data and provide accessibility to the global community. Users can plug in individual algorithms in a modular fashion, based on their needs. Both the algorithms and the derived products can be bought and sold, thus generating results on demand.

Harris Corporation (**https://www.harris.com/**) recently field tested the prototype. "When we show HICO IPS to our customers, they immediately see the value of accessing data through a web application," said Amanda O'Connor, business development manager. Users of coastal remote sensing data range from commercial fisheries that determine prime fishing locations to public health officials assessing the potential need for swim advisories.

Users need no prior knowledge of image acquisition or processing to get meaningful answers quickly, and the tool needs no calibration.

During its 5-year operation, HICO collected approximately 10,000 hyperspectral scenes of Earth, most of them available through **http://oceancolor.gsfc.nasa.gov/**. Although HICO is no longer operating, the HICO IPS framework can use other remote sensing instruments, including future imagers on the space station as well as satellites.

"HICO IPS bridges the gap between the theoretical science mission of the ISS and something people can consume and use," O'Connor added. "As a taxpayer, that makes me happy. This application is bringing return on investment to the public who helped finance the space station. That really underscores the relevancy of the ISS as a National Lab."

Space station-based Earth sensing and imaging also supports other technology, including the German Space Centre (DLR) Earth Sensing Imaging Spectrometer (DESIS), a hyperspectral sensor for the Multi-User System for Earth Sensing (MUSES). DLR and Teledyne partnered on DESIS, which is a visible to near-infrared imaging spectrometer. DESIS supports both scientific research and humanitarian and commercial purposes. Examples of its applications include land cover classification, biomass assessment, drought impact assessment, forest health monitoring, water quality monitoring and oil spill monitoring and assessment.

Artificial Intelligence for Solving Crime

Artificial intelligence, which is already helping astronauts on the ISS, is also providing a promising approach for solving crimes. In an era of security concerns, the smart use of police data is critical for uncovering leads. It can detect suspicious patterns, reconstruct scenes and highlight promising avenues of investigation. The origins of this machine intelligence date back almost 15 years, when efforts were aimed at preparing astronauts for space. The Space Applications Services company developed question-answering software for training astronauts on ESA's Columbus research laboratory.

Artificial intelligence, which is already helping astronauts on the ISS, is also providing a promising approach for solving crimes.

Artificial intelligence is set to play a major role in future space missions. More automation can reduce ground operations, costs and risks. ESA astronaut Alexander Gerst will build on previous research. He will test an intelligent mobile crew assistant following his launch to the ISS in the summer of 2018.

Although the initial crew training project of 2003–2005 provided a small step in artificial intelligence, it led to a completely different domain: security. Space Applications Services developed a tool that could cope with most factual questions and display the results. It became possible to find specific video feeds in surveillance cameras from thousands of hours of recordings. Hereafter, the same technology was used for training crisis managers at airports for real-time decision making. The staff were trained in a simulator to detect incidents and potential threats.

A decade after the space trial, European engineers started working on the semi-automated scanning of huge amounts of data from a wide range of source—e.g., written records, footage and social media—within seconds. The software does the laborious parts of a crime analyst's job with a single click. The Belgian police are now evaluating it for cost-effective intelligence gathering and analysis. The software could become a commercial product by mid 2018.

Small Computers Tackle Big Tasks in Space

Tiny processing boards perform giant tasks onboard the International Space Station. These business-card sized tools, called Q-cards, also provide rover navigation and run the payloads of many satellites.

Xiphos Technologies (**http://xiphos.com/**), a Canadian company specializing in computing and network communication for harsh environments, developed and tested the Q-card data processing technology for the space station. In addition to running conventional software code, the cards use

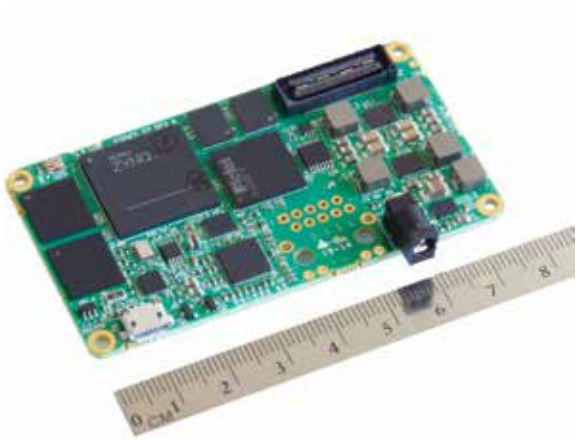
As the task of data processing grows larger and larger, space-based research is helping the make the tools for accomplishing that task smaller and smaller.

a technology called programmable logic to perform complex processing tasks at a fraction of the power and weight of conventional computers.

Q-cards have been spaceflight-proven and currently process experiment data onboard the space station. The networked processors also provide high-performance, fault-tolerant sensor processing for other spacecraft. Xiphos hardware and software are flying on several satellites and have powered Automatic Identification System (AIS) payloads in low Earth orbit for nearly ten years, allowing ships to be tracked world-wide.

A spinoff company, GHGSat (**www.ghgsat.com/**), developed nanosatellite monitoring of greenhouse gas (GHG) emissions and air quality for various industries, including oil and gas, with better accuracy and at a fraction of the cost of comparable alternatives. The company launched the world's first high-resolution satellite designed to measure GHGs in 2016 and is using this patented technology to provide GHG emissions monitoring data and services globally. GHGSat seeks to become the global reference for remote sensing of GHG, air quality gas, and other trace gas emissions from any source in the world. GHGSat's first demonstration satellite "Claire" uses a Xiphos Q7 processor card to run its complex hyperspectral payload and manage the immense amounts of data produced every day.

In addition, Xiphos spun off other successful commercial ventures, including XipLink, a technology company that provides software and hardware to speed up wireless and satellite data communications, including Internet service for remote areas and several countries.



The Q7 processor card, the latest in a product line that first flew on the ISS in 2003 and currently used for a wide range of applications including satellites, ISS experiments, and rover avionics.

*Image credit: Xiphos Technologies (***http://xiphos.com/products/q7-processor/***)*

Q-Card Processors Cast a Wide Net to Collect Emissions Data

Xiphos Technologies (10 employees, $4M est. annual revenue) has used ISS for development and demonstration of its Q-Card processors since 2004. From 2000-2016, they received $666,000 in funding from CSA for the development and commercialization of Q-cards. Two companies have been spun-off from Xiphos Technologies. XipLink (employs roughly 25, $4M est. annual revenue) specializes in optimization of data transmission over Wide Area Network (WAN) and satellite links. GHGSat (employs 40) received $2.3M in public funding from Sustainable Development Technology Canada. The GHGSat-D satellite, funded in part by Imperial Oil, Shell, Canadian Natural Resources Limited, and Suncor Energy, launched in 2016. This satellite provides information on greenhouse emissions at targeted locations for its stakeholders. As of June 2018, emissions data had been collected for over 3,000 sites.

As the task of data processing grows larger and larger, space-based research is helping the make the tools for accomplishing that task smaller and smaller.

Beyond the Cloud: Data Processing from Low-Earth Orbit

The ISS is constantly downlinking information to ground control, such as data from investigations, video footage from interior and exterior cameras, satellite imagery—anything that connects space to the ground.

As spacecraft technology continues to advance and evolve, so must the processing technology used to return information back to Earth. The SG100 Cloud Computing Payload (i.e., SG100 Cloud Computer) investigation aboard the orbiting laboratory validated a radiation-tolerant processor capable of processing data 12 times faster than any available counterpart.

An evolution of the main data computers used within the Alpha Magnetic Spectrometer-02 (AMS-02), the SG100 demonstrated the technology's ability to function in a radiation environment, providing more cost-effective spaceflight data processing opportunities for commercial researchers.

"Buying a radiation hardened computer would cost them about a million dollars, but replacing it with the SG100 will cost them about a quarter million," said Trent Martin, the investigation's primary investigator. "The economic impact to the aerospace community could be significant."

The SG100 challenges the current industry standard of radiation-hardened processors by offering radiation-tolerant processors. This small drop in processing ability leads to more than a half-million-dollar drop in price, thereby opening the doors to space even wider for commercial entities.

As spacecraft technology continues to advance and evolve, so must the processing technology used to return information back to Earth.

"Radiation hardened means no matter what, radiation will not effect this processor," said Martin. "Whereas radiation tolerant means that most likely, nothing will happen—but if it does, it won't be detrimental. The processor won't die."

No single event upsets occurred during the processor's 2-year stay aboard the laboratory. In other words, no data was lost.

Once we move past low-Earth orbit, SG100 will allow for onboard processing, rather than requiring that data be downlinked to Earth before analysis, thereby saving time and resources.

"In low-Earth orbit, we are able to shrink the data down to a minimal set before you send it down," said Martin. "In deep space, it allows you to actually you to do your processing there. Now, if we are doing the processing on Mars, rather taking the time to send it back to Earth and then back to Mars—that is 16 minutes that's just eliminated."

Developed by Business Integra (**https://www.businessintegra.com/**), the SG100 returned to Earth aboard the SpaceX-14 Dragon capsule in spring of 2018.

This investigation was sponsored by the ISS National Lab, which is managed by the Center for the Advancement of Science in Space.

The Adeli treatment suit in use for pediatric rehabilitation.

Image credit: Aerospace Medical Center and Technology, Russia

Human Health

The International Space Station is a unique laboratory for performing investigations that affect human health both in space and on Earth. During its time in orbit, the space station has enabled research that is providing a better understanding of many aspects of human health including aging, trauma, disease and environmental impacts. Driven by the need to support astronaut health, several biological and human physiological investigations have yielded important results that can benefit us here on Earth. These results include new ways to mitigate bone loss, insights into bacterial behavior, and innovative wound-healing techniques. Advances in telemedicine, disease models, psychological stress response systems, nutrition and cell behavior are just a few more examples of the benefits that have been gained from applying studies in orbit to human health back on Earth.

Health Technology

Research on the International Space Station (ISS) has allowed for innovations in surgical performance through the world's first robotic technology capable of performing surgery inside magnetic resonance imaging (MRI) machines. This technology is making difficult brain tumor surgeries easier and impossible surgeries possible. Soon, medical technology stemming from space station robotics will enter clinical trials for use in the early diagnosis and treatment of breast cancer by providing increased access, precision and dexterity resulting in highly accurate and minimally invasive procedures. Development of an advanced technology solution for pediatric surgery is also in the design stages. In common laser surgeries to correct eyesight, a new technology developed on the ISS is now used on Earth to track the patient's eye and precisely direct a laser scalpel. Thermal regulation research on the ISS has also led to the use of sensor technology for monitoring during surgery.

When medical facilities are not readily available such as in remote and underdeveloped regions of the world, ultrasound units are used in conjunction with protocols for performing complex procedures rapidly with remote expert guidance and training. These telemedicine and remote guidance techniques empower local healthcare providers, provide patients with access to more timely and diagnostic care, and make the healthcare system more efficient.

A lightweight, easy-to-use device to measure nitric oxide in air exhaled by astronauts on the ISS is used to study possible airway inflammation before health problems are encountered. This device is now used at some health centers to monitor levels of asthma control leading to more accurate medication dosing, reduced attacks, and improved quality of life.

The study of plasmas (i.e., charged gases that can permeate many materials and spread evenly and quickly) reveals that they support the disinfecting of chronic wounds, the neutralization of bacteria, the boosting of tumor inactivation, and even the jumpstarting of plant growth.

Space Station Robotic Arms Have a Long Reach

The technology behind a robotic arm used to assemble the football-field-sized ISS also powers robotic tools that help to perform delicate surgeries on Earth.

Canadarm, first launched into space on the Space Shuttle Columbia (STS-2) on November 13, 1981, made 90 flights over the course of the next 30 years. Canadarm2, the next-generation version launched in 2001, was a crucial tool in assembling the space station and continues to be used to move supplies, equipment and even astronauts. It also supports space station maintenance and upkeep and performs "cosmic catches"—capturing and docking unpiloted spacecraft that deliver science payloads and cargo to the space station.

The technology behind a robotic arm used to assemble the football-field-sized ISS also powers robotic tools that help to perform delicate surgeries on Earth.

Dextre, a robotic handyman, arrived at the space station in 2008. Dextre can ride on the end of Canadarm2, thereby reducing the need for risky spacewalks to conduct routine chores and freeing up astronaut time for science—the main function of the space station. Dextre also provides a unique testing ground for new robotics concepts such as servicing satellites in space. Robotic experts at the Canadian Space Agency (CSA) and NASA guide these space robots as they go about their tasks.

Canadian expertise in automation, robotics and imaging has also inspired development of cutting-edge spinoff technologies for industry, medicine and other applications on Earth. In medicine, for example, related technology transformed the way surgery is performed, with tools such as neuroArm, which

is an image-guided, computer-assisted neurosurgery device, and the Image-Guided Autonomous Robot (IGAR), which is a digital surgical tool that provides increased access, precision and dexterity for performing highly accurate, minimally invasive procedures.

Canadian space robotics technology also led to BrightMatter™ Drive—a robotic digital microscope developed by Toronto-based Synaptive Medical in partnership with Canadian robotics leader MacDonald, Dettwiler and Associates (MDA), a Maxar Technologies company and CSA's partner in designing the Canadarms. Drive features some of the same software as Canadarm2 to help neurosurgeons perform minimally invasive clinical procedures with greater safety and efficiency. Drive launched in 2015, and feedback from surgeons within partner hospitals guided Synaptive to create the second-generation microscope, Modus V™, which was launched in October 2017 in North America and became globally available in August 2018.

Modus V is being used to help to treat patients with a variety of brain and spine conditions in hospitals across North America, providing surgeons with an optimal view of the surgical field through high-powered optics. The automated digital microscope moves seamlessly and tracks the surgeon's tools to maintain focus on the procedure and helps to shorten procedure times by minimizing the need for surgeons to make manual adjustments. Large screens provide the surgical team with a holistic, collaborative view of the patient's brain and spine. Used in combination with other Synaptive technologies, Modus V may allow surgeons to operate on brain tumors previously deemed inoperable.

The journey from a 17-m (55-ft) arm in space to high-powered microscopic images of the human brain, it turns out, runs through the space station.

Applying Space Technology used to Power Automated Surgery

Synaptive Medical and MDA collaborated to engineer the Modus V™ —a commercially available digital robotic microscope designed using principles of the International Space Station's Canadarm2 technology. Currently used in leading healthcare centers, research institutions and community hospitals across North America, the Modus V has the potential to offer brain surgery to patients considered inoperable using other methods, and may potentially improve spinal surgery methods by lowering the risk of complications and by reducing recovery time. As of this publication, Modus V has been used to treat more than 1,000 cases during its 8 months on the market; Synaptive's BrightMatter technology has been used in more than 5,000 cases.

Robotic Arms Lend a Healing Touch

The delicate touch that successfully removed an egg-shaped tumor from Paige Nickason's brain got a helping hand from a world-renowned arm—a robotic arm, that is. The technology that went into developing neuroArm—the world's first robot capable of performing surgery inside magnetic resonance imaging (MRI) machines—was born of the Canadarm (developed in collaboration with engineers at MDA for the U.S. Space Shuttle Program) as well as Canadarm2 and Dextre, the CSA's family of space robots performing the heavy lifting and maintenance aboard the ISS.

The development of neuroArm began with the search for a solution to a surgical dilemma: Is it possible to perform surgery within the bore of a magnet—i.e., an MRI system—while imaging is being acquired? Towards this, MDA worked with a team led by Dr. Garnette Sutherland, Professor of Neurosurgery at the University of Calgary, to develop a highly precise robotic system that works in conjunction with the advanced imaging capabilities of MRI systems. This required designing a robot that was as dexterous as the human hand, precise, accurate and without tremor. For safety, the system had to be built from

The image-guided autonomous robot (IGAR) will provide increased access, precision and dexterity, resulting in more-accurate and less-invasive procedures.

Surgeons and engineers sought to improve the safety of surgery by merging machine technology with advanced imaging! "Where the robot entered my head," says 21-year-old Paige Nickason, the first patient to have brain surgery performed by a robot, as she points to an area on her forehead. "Now that neuroArm has removed the tumor from my brain, it will go on to help many other people like me around the world."

Image credit: University of Calgary

MR-compatible materials—for instance, ceramic motors—so that operation of the robot would not be affected by the magnetic field of the MRI or, conversely, impact the acquired image quality. In addition, the system included advanced haptics, safety no-go zones, motion scaling and tremor filter. This innovative team developed novel ways to control the robot's maneuvers and give the operator a sense of touch via an intuitive, haptic hand-controller located at a remote work station, which is essential so that the surgeon can precisely control the robot and can feel the tool-tissue interaction during surgery. Thus, Health Technology Research on the ISS provided the innovations necessary for robotic brain surgery through neuroArm. Capable of microsurgery and sterreotaxy, this technology is able to not only introduce disruptive ideas into the operating room, but also increase the safety of surgery.

Since Paige Nickason's surgery in 2008, neuroArm has been used in initial clinical experiences with 85 patients suffering from various neurosurgical conditions including brain tumors and vascular malformations. In 2010, the neuroArm technology was licensed to IMRIS Inc., a private, publicly traded medical device manufacturer

Medical team prepares neuroArm Surgical System for use in the operating room.

Image credit: University of Calgary

based in Winnipeg, Manitoba, Canada, for development of the next-generation platform and for wide distribution under the name SYMBIS Surgical System.

IMRIS, working with MDA, is advancing the design to commercialize minimally invasive brain surgery by adding advanced haptics augmented three-dimensional (3-D) vision and novel toolset to the system. SYMBIS has been undergoing calibration, testing and validation at Dr. Sutherland's research facility since March 2015. SYMBIS has already received FDA approval for stereotactic biopsy within the bore of the magnet while real-time magnetic resonance images are being

Dr. Garnette Sutherland, with neuroArm, his brainchild, in the 3.0T iMRI suite at Foothills Medical Centre, Calgary.

Image credit: Project neuroArm, University of Calgary

Dr. Garnette Sutherland, with the SYMBIS system in his Experimental Operating Room at Project neuroArm, University of Calgary.

Image credit: Project neuroArm, University of Calgary

acquired. With clinical experience from neuroArm, followed by knowledge from SYMBIS, Dr. Sutherland's team is currently developing the third-generation neuroArm called neuroArmPlus, an advanced surgical robotic systems for whole body application. SYMBIS received approval from the Food and Drug Administration in 2015 for use in stereotactic brain biopsy procedures.

In collaboration with the Centre for Surgical Invention and Innovation (CSII) in Hamilton, Ontario, MDA is also developing an advanced platform to provide a more-accurate and less-invasive identification and treatment of breast tumors in the MRI. The image-guided autonomous robot (IGAR) will provide increased access, precision and dexterity, resulting in more-accurate and less-invasive procedures. IGAR is currently in the second phase of clinical trials in Hamilton and in Quebec City.

Learn more here:
IGAR: **http://tinyurl.com/CSA-IGAR**

Humans and Robots: A Partnership with Myriad Medical Benefits

Although human surgeons currently possess superior speed and dexterity, neuroArm's workstation has proven positive implications for technology management and surgical education, and is a step toward a future in which a variety of machines are merged with medicine to improve patient outcomes.

Robots from Space Lead to One-stop Breast Cancer Diagnosis Treatment

Technology derived from the highly capable robots designed for the ISS may soon increase access to life-saving surgical techniques to fight breast cancer.

A team of collaborative researchers with CSII in Canada is working to enhance the quality of, and access to, healthcare through the development and commercialization of innovative medical robotic technologies. One advanced platform in particular is about to enter clinical trials for use in the early diagnosis and treatment of breast cancer.

The main player besides the medical staff is a robot. But not just any robot: IGAR. MDA designed this robot's technology for the CSA for use aboard the ISS by MacDonald, Dettwiler and Associates Ltd. (MDA), a Maxar Technologies company, for the Canadian Space Agency (CSA).

Researchers created IGAR from a long line of Canadian heavy lifters and maintenance performers for the space shuttle and space station Canadarm, Canadarm2 and Dextre. In dealing with breast cancer, IGAR is expected to provide increased access, precision and dexterity, resulting in highly accurate and minimally invasive procedures.

A team of collaborative researchers with CSII in Canada is working to enhance the quality of, and access to, healthcare through the development and commercialization of innovative medical robotic technologies.

Dr. Mehran Anvari, chief executive officer and scientific director at the CSII, with the IGAR manipulator.

Image credit: The Hamilton Spectator

Dr. Mehran Anvari, chief executive officer and scientific director at CSII, said the IGAR platform moves the use of robotics in surgery to a new dimension, allowing the robot to act in an automated fashion after it is programmed by a physician.

IGAR is designed to work in combination with an MRI scanner, which is highly sensitive to early detection of suspicious breast lesions before they possibly turn into a much larger problem. The radiologist uses specially designed software to tag the potential target and tell IGAR what path to take. The software then helps the radiologist make sure he or she is accurately hitting the right area. IGAR has a special tool interface that can be used to define adaptors for any needle-based biopsy device or a wide range of instruments that remove tissue, known in the medical world as needle-based ablation devices.

Anvari explained that the automated robot is capable of placing the biopsy and ablation tools within 1 mm of the lesion in question with a high degree of targeting accuracy, improving sampling, reducing the pain of the procedure, reducing time in the MRI suite and reducing cost as a consequence. He also said that using the robot will allow all radiologists to perform this procedure equally well, regardless of the number of cases per year, and move the site of treatment from operation room to radiology suite for a significant number of patients. The radiologist can operate in the challenging magnetic environment of the MRI, providing access to leading tumor-targeting technology. The robot fits on the patient bed, so it can travel in and out of the MRI opening easily. This in turn simplifies the flow of patients in the department, which can be challenging to many radiologists, thereby optimizing patient time to diagnose.

Dr. Nathalie Duchesne, co-investigator on the clinical study and breast radiologist at the Saint-Sacrament Hospital in Quebec City, Quebec, Canada, has been teaching MRI-guided breast biopsy for years and will be performing the first of three clinical trials. She said that many steps in the procedure are operator-dependent, and these steps may prevent good sampling of the lesions if not done properly. Duchesne believes IGAR will decrease the time of the exam, ensure good sampling and increase patient's comfort during the exam. Duchesne and her team think that IGAR will improve sample collection because it will be less operator-dependent, and it will be constant from one doctor to another, from one patient to the other, and from one lesion to the other.

IGAR manipulator and full breast intervention platform mounted on the patient support structure with a biopsy tool attached.

Image credit: CSII and MDA

Artist rendering of IGAR performing a biopsy.

Image credit: CSII and MDA

IGAR removes most of the "manual" aspects of the procedure and reduces user dependence and the level of training required. This allows for a standard process regardless of experience. An expert will program remotely once the patient is in the MRI suite. A physician will then supervise to make sure the patient is comfortable and that no complications occur.

Anvari said this technology lays the foundation for a family of telerobotic systems, has the potential to change the way people think about performing these interventions, and ensures that specialized, highly-trained doctors are focusing on the activities to which their training is best suited. Anvari believes this technology will improve efficiency in the health care system by streamlining clinical workflow and allowing highly skilled radiologists to extend their care to a wider population through teleoperation.

This robotic technology is not limited to biopsies. Duchesne explained that IGAR is paving the way for the minimally invasive excision and treatment of small tumors that are often found incidentally during pre-op MRI.

The trend toward breast preservation has brought on the importance of lumpectomies. For tumors that may require this procedure because they are invisible to ultrasound and X-ray mammography, researchers are currently developing the ability for IGAR to deploy a radioactive seed—smaller than a grain of rice—near the area of interest. During surgery, the seed can be located with a detector, allowing the doctor to identify the lesion and remove it with increased accuracy and patient comfort. It is expected that follow-up surgeries also will be greatly reduced.

Whether it be capturing a visiting spacecraft or helping save lives, Canadian-designed robots are lending a hand. Bringing beneficial technologies from the space station to the ground will hopefully one day allow us to make historic strides in cancer treatment.

Watch this video to learn more about IGAR:
http://tinyurl.com/CSA-IGAR

Improved Eye Surgery with Space Hardware

Laser surgery to correct eyesight is common practice, 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.

When looking at a fixed point while tilting or shaking one's head, a reflex allows the eyes to automatically hold steady and see clearly even while this movement is taking place. This involves the brain constantly interpreting 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.

Tracking the eye's position without interfering with the surgeon's work is essential in laser surgery.

The Eye Tracking Device experiment researched mechanisms involved in this process and how humans' frames of reference are altered in space. The experiment used a specially designed headset fitted with high-performance, image-processing chips able to track the eyes without interfering with an astronaut's normal work. The results showed that our balance and the overall control of eye movements are indeed affected by weightlessness. These two systems work closely together under normal gravity conditions but become somewhat dissociated in weightlessness. After a flight, it takes several days to weeks for the astronauts to return to normal. The findings point to the entire sensory-motor

Former ESA astronaut Thomas Reiter undertakes the Eye Tracking Device experiment on the ISS in 2006.

Image credit: ESA

Robotics Help Bring Eye Surgery into Greater Focus

More than 2000 Chronos Eye-Tracking Devices were sold to clinics and hospitals between 2004 and 2014, and around 30 to 40 leading laboratories for vestibular research and neurology have used, or are still using, the system to perform ground-based studies. During the active marketing phase, the technology accounted for 40% to 60% of company turnover and generated $15 million in turnover overall. Chronos Vision is now developing a new application in which the experience from the eye tracker technique is an important feature that is primarily aimed at eye lens replacement procedures (e.g., during cataract surgery). The primary focus is guided surgery for personalized (i.e., toric) lenses, which are an improvement on standard intraocular lenses, by taking into account the aspheric nature of the cornea.

complex and spatial perception relying on gravity as a reference for orientation.

The engineers realized the device had potential for applications on Earth in parallel with its use on the space station. Tracking the eye's position without interfering with the surgeon's work is essential in laser surgery. The space technology proved ideal, and the Eye Tracking Device equipment is now being used in a large portion of corrective laser surgeries throughout the world. A commercially available version has been delivered to several research laboratories in Europe and North America for ground-based studies.

The Art—and Science—of Detecting Chromosome Damage

Art meets science in a technique that highlights or paints certain areas of a chromosome to detect damage. These paintings could help protect the health of astronauts in space.

Abnormal changes in chromosomes, including types called translocations and inversions, can have profound genetic effects, such as disrupting regulatory sequences that control gene expression. Ionizing radiation is known to induce these chromosome aberrations, which also play a role in triggering cancer. The exposure of astronauts to space radiation makes detecting such changes an important part of maintaining their health.

Chromosomal inversions in particular, especially small ones, have been historically difficult if not impossible to detect. With funding from NASA, KromaTiD Inc. successfully demonstrated detection of these small chromosomal inversions using a technology called chromatid painting. A NASA Human Research investigation, Chromatid Paints, demonstrated use of the technology to highlight certain areas of a chromosome by using increased resolution to more precisely detect structural changes over time in those on extended missions in space. It works for the general population on Earth as well.

The chromatid paint approach increases sensitivity of chromosome analysis by adding a new class of observable aberrations.

Although some large detectable chromosome inversions have known association with certain cancers, adequate investigation of these cancer-specific chromosomal inversions is currently not possible. This means many such inversions, especially small ones, likely remain undiscovered. Small inversions are likely to be among the most common and most stable chromosome aberrations created by charged particle radiation exposure. The chromatid paint technique therefore could contribute to risk analysis by revealing, for the first time, these small and previously cryptic (i.e., hard to find) yet predictable cancer-related inversions.

"We expect that chromatid paints will fulfill multiple needs in several fields related to human health,"

The chromatid paint approach increases sensitivity of chromosome analysis by adding a new class of observable aberrations.

says Principal Investigator Edwin Goodwin, one of the founders of KromaTiD.

Other potential applications include screening cancer cells for previously undetected inversions that played a role in causing the cancer. Identification of these new, cancer-specific inversions may lead to better diagnostic and prognostic tests and, eventually, drug targeting. Other possibilities include clinical cytogenetics and biomedical research such as studies of cancer induction, radiation effects and chemical toxicology. The technology also could evaluate radiation exposure occurring accidentally or from a terrorist attack.

Researchers continue to develop the next generation of chromatid paints, using a faster, more cost-effective approach. Ultimately, multi-color chromatid paints can cover the entire genome, thereby providing identification of translocations and simultaneous and sensitive detection of inversions. Next-generation chromatid paints offer higher resolution than currently possible, thus greatly expanding potential applications.

Inversions are highly stable in an individual's cells and therefore can also serve as biomarkers of previous damage long after that damage occurred. In addition to monitoring DNA damage in astronauts after they return from space, the technology could be useful in professions that may expose personnel to radiation or other potential cancer-causing agents. The painting technique also may lead to the discovery of inversions associated with other diseases and autism. That would be a pretty picture, indeed.

NASA Twins Study Used to Validate Chromosomal Painting Technology

Biotechnology company KromaTid was initially funded via two grants, totaling $700,000, sponsored by NASA's Human Research Program. The grants were intended to mature technology for analysis of lymphocytes obtained from astronauts to improve space radiation risk analysis. As part of the validation for its chromosomal inversion technology, the company's chromatid painting system was used in the high-profile NASA International Space Station twin study in 2015. As of 2018, KromaTiD has raised $8.35 million, been granted three US patents, published four scientific papers, and launched distribution partnerships with Tokyo Future Style and Tebu-Bio in Japan and Europe, respectively.

Sensor Technologies for High-pressure Jobs and Operations

Novel sensor technologies used within the joint Thermolab experiment (2009-2012) of German Aerospace Center Deutschen Zentrum für Luft und Raumfahrt (DLR)/European Space Agency (ESA) have been used for improving our understanding of thermal regulation of astronauts in space. These sensor technologies also hold great potential and benefits for use within many different critical areas from firefighting to recognizing exhaustion or early overheating. In fact, the sensor is currently used in hospitals for monitoring during surgeries and on intensive care units.

Thermal regulation in the body is vital for our well-being. Our vital organs are kept at a constant temperature of 37°C (98.6°F) whether it is the middle of a freezing winter or on a hot sunny beach. Any disturbance to this stasis can cause symptoms such as physical and mental fatigue or, in the extreme, fatal effects on how the body functions under conditions such as heat stroke and hypothermia. Heat stress is of particular and growing concern in various occupational settings. A World Health Organization scientific group on health factors concluded that "it is inadvisable for deep body temperature to exceed 38°C in prolonged daily exposure to heavy work."

On Earth, firefighters, jet pilots, miners, steel workers, soldiers in combat, divers, mountaineers, polar explorers, marine fishermen, and all who work in extreme conditions could benefit from the new measurement technology.

In weightlessness, this becomes significant as heat transfer processes are considerably challenged as reduced gravity impairs convective heat transfer and the efficiency of evaporation. The Thermolab experiment looked at changes in thermal regulation (and cardiovascular adaptations) in weightlessness by investigating how the body heats up and cools down during exercise. The testing of the new type of sensor to record the core body temperature in orbit could have novel applications in space and on Earth. This new sensor was developed for DLR by Charité (Berlin) and Draegerwerk (Lübeck) since standard ground measurement in clinics and surgeries use an internal body probe for taking measurements, which is not practical in orbit. The sensors measure the skin temperature and the heat flow in the skin, which are used to calculate core body temperature using sophisticated algorithms.

Core body temperature rises higher and faster during exercise on the International Space Station compared to how it rises on Earth. This is likely caused by fluid shifts and modified heat flow away from the body. Moreover, for the first time, a sustained increase in astronauts' core body temperature was observed under resting conditions. This increase of about 1°C developed gradually over 2.5 months and was associated with increased concentrations of a key anti-inflammatory protein. Since even minor increases in core body temperature can impair physical and cognitive performance, both findings have a considerable impact on astronauts' health and well-being during future long-term spaceflight. Furthermore, data indicated that the impairments in thermoregulation are still prevalent after return to Earth, and recovery occurs very gradually. With exercise being a vital spaceflight countermeasure, and with greater than 80% of energy expenditure during exercise converted to heat, investigating the effects of long-duration spaceflight on core body temperature at rest and during exercise become significant. Irrespective of its underlying causes, this space fever, as we may call it, has potential implications for long-term spaceflights in terms of astronauts' health, well-being and support, including energy, nutrient and fluid requirements as well as physical and cognitive performance.

The measurement of the core body temperature together with cardiovascular measurements taken during NASA's VO2 Max (i.e., maximum rate of oxygen consumption measured during incremental exercise) protocol can be used to evaluate the subject's state of fatigue, which is very important during a space mission for optimizing mission success. This non-

Non-invasive Sensors get to the "Core" of Body Temperature Changes

Research garnered from the Thermolab experiment has resulted in at least seven scientific publications. The direct line of this Deutschen Zentrum für Luft und Raumfahrt (German Aerospace Center)/European Space Agency-supported research led to the development of a non-invasive core body temperature measurement technology—the double sensor. Double sensor technology accounts for 10 patents and has been incorporated into Tcore—a Dräger Medical product currently used in hospitals for monitoring during surgeries and on intensive care units. The benefit of skin-based temperature monitoring is acutely realized in these areas, where the minute-to-minute changes in core body temperature provide critical information—especially where traditional invasive thermometers may not be accepted or used by care providers.

Sweat the Small Stuff: Minor Changes in Core Body Temperature Impair Performance

Thermolab examined core body temperature in microgravity during periods of exercise and rest and found an increase of 1°C, thereby demonstrating that even minor changes can impair physical and cognitive performance. These findings indicate significant challenges must be overcome before humans can embark on long-duration exploration missions beyond low-Earth orbit.

invasive double sensor is a highly useful diagnostic tool for recognizing early warning signs of fatigue during spacewalks in orbit. On Earth, firefighters, jet pilots, miners, steel workers, soldiers in combat, divers, mountaineers, polar explorers, marine fishermen, and all who work in extreme conditions could benefit from the new measurement technology. It could also be used for monitoring during critical hospital operations such as heart surgery or for monitoring babies in incubators.

Non-invasive Collection of Saliva Helps Monitor Stress Levels in Real Time

Spitting is discouraged aboard the ISS, unless it helps monitor the health of crew members. However, while saliva samples can be useful for such monitoring, storing them for later analysis on Earth is expensive and cumbersome, and means any problems that are identified cannot be addressed in a timely manner.

Increased stress is a common problem associated with spaceflight. The ISS Non-invasive Sample Investigation and results Transmission to ground with the Utmost easiness (IN SITU) investigation tested a portable device to conduct direct, real-time analysis of saliva samples on the space station. Investigators used the device to monitor stress levels among crew members by detecting the presence of the stress hormone cortisol.

The IN SITU device uses disposable cartridges, and sample collections and analyses are simple to perform. Crew members collect saliva with a swab, inject the sample into the cartridge, and push buttons to initiate the analytical procedure. They then insert the cartridge into a reader to obtain results. The process poses no risk to the operator or the space station environment. Since this process relies on capillary forces, it is not affected by microgravity conditions. The device makes sensitive and specific quantitative measurement of biomarkers possible by using fluid samples obtained non-invasively.

A miniature analytical device for detecting specific biomarkers in samples collected non-invasively has significant potential benefits on Earth as well.

Paolo Nespoli performs the IN SITU experiment onboard the space station.

Image credit: NASA

"Saliva is easily and non-invasively collected, especially in microgravity," said Principal Investigator Aldo Roda of Italy's University of Bologna. "It does not require cumbersome pre-analytical treatment procedures; in this case, it was analyzed as is. Moreover, it is a particularly interesting matrix for measuring cortisol, since data in the literature already demonstrate that salivary levels of cortisol well correlate with its blood levels."

In addition to improving crew health monitoring on the space station, the device could be employed to monitor astronauts on long-duration missions to Mars, asteroids or other distant destinations.

Simple modification of the cartridges would make it possible to analyze other biological fluids, such as blood, plasma and sweat.

"In principal, the cartridge could be used to detect any biomarker measurable by an immunological method," said Roda. "That includes other hormones, peptides, proteins and even drugs." Analysis could be expanded to include biomarkers of inflammation, infection, bone loss, muscle atrophy, cardiovascular disorders and other physiological changes that astronauts often experience during spaceflight.

A miniature analytical device for detecting specific biomarkers in samples collected non-invasively has significant potential benefits on Earth as well. It can be employed in any situation where rapid access

to an equipped laboratory is not available, such as in ambulances, emergency situations, developing countries, remote locations, or at a patient's bedside. The disposable cartridge is created using 3-D printing technology, which further expands its potential value in nontraditional settings.

The project was supported by the Italian Space Agency (ASI) and by experiments conducted using ASI resources onboard the space station.

The cartridge reader remains onboard the space station, making it possible to prepare and deliver cartridges that are modified for other analyses. A potential improvement would be substituting a smartphone or tablet for the reader by using existing camera technology in these devices to acquire a chemi-luminescent signal and a dedicated app for results output.

The potential advantages of this device are definitely worth salivating over.

Cold Plasmas Assist in Wound Healing

In recent years, health experts have seen a dramatic rise in super-strains of bacteria that can survive the strongest antibiotics in medicine's arsenal. Technology developed for performing research on the ISS has helped develop plasma-based devices to fight superbugs on Earth.

Cold plasma therapy provides a new way to keep hospital patients safe from infections. This technology spin-off from space hardware knocks out bacteria without damaging human tissue, thereby accelerating the process of wound healing. Cold plasma has many practical applications—from food hygiene, to treatment of different kinds of skin diseases, to the purification of water in developing regions. Fundamental research in orbit led to the miniaturization of devices that can be operated at room temperature.

Complex plasma research has been taking place onboard the ISS since 2001. This research has improved our fundamental knowledge and provided tremendous insights in complex plasma research and how we can control complex plasmas (i.e., plasmas mixed with fine particles). The weightless environment is ideal for this area of research by allowing astronauts to produce macroscopic analogues of atomic structure in gases and liquids and observe phase transitions such as melting or freezing.

A DC plasma source was specifically designed for space research into complex plasma and is incorporated in the ESA/ROSCOSMOS PK-4 instrument currently on the ISS. On Earth, the resulting increased know-how in plasma technology has allowed the further development of different applications. Because plasma is a charged gas, it can permeate many materials, and spreads evenly and quickly. It can disinfect surfaces, and has been proven to neutralize drug-resistant bacteria such as methicillin-resistant Staphylococcus aureus within seconds. In addition to bacteria, cold plasmas have the properties needed to safely and efficiently inactivate fungi, viruses, spores and odor molecules. In more than 3,500 examples in several clinical trials, physicians found plasmas can disinfect chronic wounds and help wounds heal faster. This revolution in healthcare has many application areas: medical technology, water treatment, odor management and hygiene.

Submarine crews and staff working in isolation for long periods could also benefit from cold plasma treatments.

Technology developed for performing research on the ISS has helped develop plasma-based devices to fight superbugs on Earth.

Side view of a plasma crystal in the laboratory. Dust particles are suspended in an argon plasma above a high-frequency electrode (bottom). The horizontal field of view is 2 cm.

Image credit: Max Planck Institute for Extraterrestrial Physics

The Hottest New Technology: Cold Plasma

Technical know-how gained during International Space Station research in the field of cold plasmas has led to the creation of three companies: terraplasma (active in hygiene, medicine, water purification, odor control); terraplasma emission control (active in car exhaust technology); and terraplasma medical (active in wound and skin disease treatment). Terraplasma holds three patents for cold plasma-based dental applications, odor removal, and homogenous plasma production. In addition, terraplasma is the exclusive licensee of seven patent families from the Max Planck Society. Following clinical validation, SteriPlas—a small ergonometric hospital treatment device for wound management—is planned for commercial release in fall 2018. Additional products in development include Plasma Care—a miniaturized wound treatment device that can create plasma from ambient air without using a gas tank.

This technology might one day make it into our homes. In space, it can provide huge benefits for astronaut health such as treating skin ailments, or for hygiene and the purification of water.

The percentage of people affected by chronic wounds is rising, especially among the ageing population. A start-up company, terraplasma medical GmbH, is now focused on developing a small ergonometric hospital treatment device for chronic wounds. The first cold plasma devices will be available by the end of 2018 to hospitals worldwide.

Understanding Asthma from Space

Help may be on the way for the millions of people around the world who suffer from asthma. Pioneering research in orbit is opening new avenues to understanding what goes wrong in patients with airway inflammation. The results have contributed to the development of quick lung tests for an improved quality of life—both on Earth and in space. With each lungful of air, our bodies absorb oxygen and exhale waste products. In people with asthma, inflammation in the lung adds nitric oxide to exhaled air. Doctors measure the amount of nitric oxide exhaled by patients to help diagnose inflamed lungs and asthma.

Pioneering research in orbit is opening new avenues to understanding what goes wrong in patients with airway inflammation.

Astronauts on the ISS have been breathing for the sake of science as part of ESA-sponsored research. Under the scientific lead of Lars Karlsson from the

Former European Space Agency (ESA) astronaut Thomas Reiter undertakes science activities for the Nitric Oxide Analyzer experiment in 2006.

Image credit: ESA

Karolinska Institute in Sweden, this research has been ongoing for more than 10 years, most recently within the Airway Monitoring experiments. These experiments analyze the amount of nitric oxide exhaled by astronauts under different conditions in the weightless environment of space (e.g., normal pressure, reduced pressure in an airlock, pre-/post-spacewalk etc.)

The astronauts breathe into a specially developed instrument that measures nitric oxide levels. The purpose of taking reduced measurements in an airlock—normally used to exit a spacecraft for spacewalks, and is set at a 30% reduced pressure—is to simulate conditions in future habitats on Mars, and is equivalent to being at 3000 m (9843 ft) altitude on Earth.

The device that measures the nitric oxide is lightweight, easy to use and accurate. The same instrument is currently used in clinics and hospitals, helping asthmatics and offering a quick and cheap way to diagnose lung problems. It was developed in close collaboration between the medical technology industry and the researchers at Karolinska Institute.

In a similar collaboration with the pharmaceutical industry, the same researchers developed a nitric oxide-donating drug (Supernitro) with a uniquely selective effect in lung circulation. The drug widens the blood vessels and counteracts life-threating increases of the local blood pressure.

On the moon and on Mars, astronaut's lungs may become easily irritated or inflamed by dust particles. The reduced gravity on those celestial bodies makes floating dust a real threat for humans.

Understanding the effects of weightlessness and reduced pressure on airway health will help space explorers monitor, diagnose and treat lung inflammation during spaceflight. This information is key to ensuring the health and safety of astronauts on longer missions beyond Earth's orbit.

Measurable Monitoring Technology; Immeasurable Possibilities

Monitoring technology used to measure the fractionally exhaled nitric oxide (FeNO) content produced by astronauts has led to a line of commercial devices. Aerocrine's NIOX MINO has been used to complete more than 10 million tests since 2004, whereas NIOX VERO was introduced in 2014. In 2015, Circassia Pharmaceuticals acquired Aerocrine for $214 million. In 2017, these NIOX devices were the leading point-of-care FeNO monitoring products, used to perform approximately 3.6 million tests annually in more than 8,700 locations worldwide, with total sales of $35.9 million in 2017—an increase of 18% over 2016.

Bringing Space Station Ultrasound to the Ends of the Earth

Fast, efficient and readily available medical attention is key to survival in a health emergency. When a person is stricken with injury or illness, getting a quick and accurate diagnosis through medical imaging technology can be crucial for ensuring proper treatment.

For people who live in major cities and towns where fully equipped hospitals are only a quick ambulance ride away, that is not usually a problem. However, for those without medical facilities within easy reach, it can mean the difference between life and death.

For astronauts in orbit about 386 kilometers (240 miles) above Earth aboard the ISS, that problem was addressed through the Advanced Diagnostic Ultrasound in Microgravity (ADUM) investigation. Space station astronauts are trained to use a small ultrasound unit aboard the space station 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. Launched in 2011, the ultrasound unit used for ADUM was replaced with a smaller and even more sophisticated scanner dubbed Ultrasound 2, which is currently in use aboard the ISS.

Space station astronauts are trained to use a small ultrasound unit aboard the space station to examine fellow crew members.

NASA astronaut Tom Marshburn assists CSA astronaut Chris Hadfield with an Ultrasound 2 scan in the Columbus Module of the ISS.

Image credit: NASA

WINFOCUS and Henry Ford Innovation Institute members, Dr. Luca Neri and Alberta Spreafic, 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.

Image credit: WINFOCUS/Missions of Grace

Those same techniques are now being adapted and used for people living in remote, underdeveloped areas where CT scans, MRIs and even simple X-ray exams are impossible. In partnership with the World Interactive Network Focused on Critical Ultrasound (WINFOCUS), ADUM Principal Investigator Scott Dulchavsky, M.D., is taking techniques originally developed for space station astronauts and adapting them for use in Earth's farthest corners by developing protocols for rapidly performing complex procedures with remote expert guidance and training.

WINFOCUS is a global network organization whose main goal is to use ultrasound as an enabling point-of-care device in an effort to make medical care more accessible in remote regions. Using the ADUM methods, WINFOCUS has trained more than 20,000 physicians and physician extenders in 68 countries. These include two important holistic healthcare projects: in remote areas of Nicaragua (from 2011); and in a statewide healthcare project in Brazil, in partnership with the Secretary of Health of the State of Minas Gerais (since 2012).

WINFOCUS has also benefited from the tele-medicine and remote guidance techniques developed for use on the space station, and has adapted and further developed them to allow large-scale integration in healthcare systems on Earth through low-cost applications. Local healthcare providers are empowered, more patients can access quality and timely diagnostic care, and the healthcare system is made more accessible and efficient.

The impact of ADUM is also felt in modern emergency rooms by proving the effectiveness of ultrasound in diagnosing conditions previously considered beyond its technical capabilities, such as a collapsed lung. The ultrasound has now become integrated as a standard of care in medical treatments. In addition, the 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.

The ADUM investigation and the WINFOCUS partnership have brought the promise of space station research back down to Earth in perhaps the most direct and immediate way possible—by keeping people healthy and alive, even in remote regions where care was previously a limited option.

Giving Voice to People with Disabilities

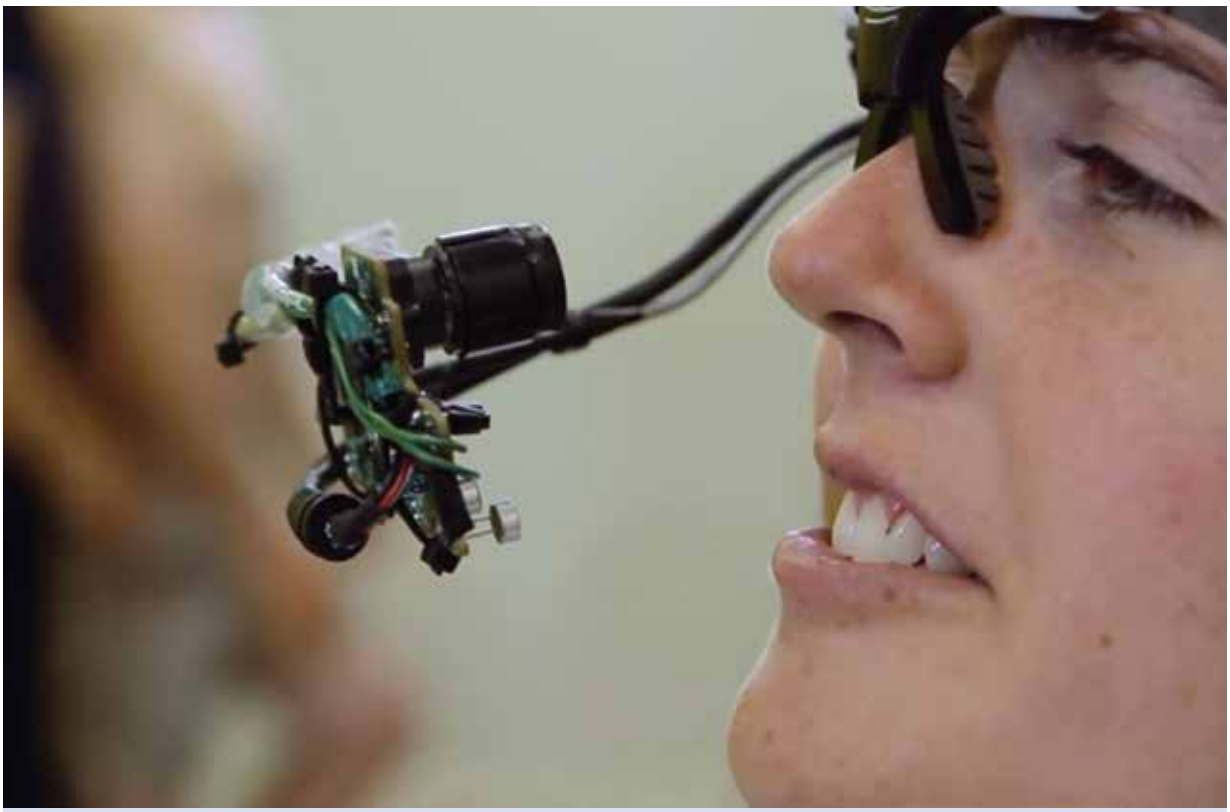
When his father was diagnosed with a debilitating disease a few years ago, it sparked Ivo Vieira into developing a novel means of communication for people coping with extreme limitations, building on visualization tools originally explored to help ESA astronauts in space. Amyotrophic lateral sclerosis and other forms of motor neurone disease gradually rob sufferers of their muscular function, including the ability to communicate verbally. However, eye movement presents an opportunity because it usually remains unimpaired.

Astronauts have only relatively rudimentary systems available during spacewalks, with only a written checklist and voice communications. A new mobile communication system based in augmented reality that has been developed for astronauts gives disabled people back their independence and human right to communicate freely. This ESA effort led LusoSpace to produce its first pair of augmented reality glasses in 2008, and to develop them for motor-impaired patients.

A new mobile communication system based in augmented reality that has been developed for astronauts gives disabled people back their independence and human right to communicate freely.

This is the first such device that is stand-alone and can be used in any location and physical position, regardless of the orientation of the wearer's head.

EyeSpeak is a direct spin-off from the work LusoSpace did for an ESA study on visualization tools for



Testing eye tracking.
Image credit: LusoVu

astronauts. The glasses detect movement of the eyes across a virtual keyboard that is displayed on the inside of its lenses. Words and phrases spelled out by the wearer are translated by the built-in software and spoken through speakers in one arm. The glasses can also let the user navigate the Internet, watch videos and access emails privately, as only the user sees what is being projected inside the lens. Since the digital information is overlaid on the lens, users can still see what is going on around them.

Helping people with extreme mobility and communication limitations is the most important impact of this technology on human lives. A spin-off company, LusoVu, was set up as a result of the EyeSpeak development. The team is exploring the downstream markets for visualization display system technologies. One idea is for use in logistics warehouses, where head-mounted displays would substantially improve workers' productivity in the picking process. Potential upgrades include allowing users to control their wheelchair and other things in their environment, such as air conditioning or televisions.

When it Comes to Communication, the Eyes Have It

Augmented reality glasses engineered by LusoSpace to help European Space Agency (ESA) astronauts on the International Space Station led to a spin-off company, LusoVu. LusoVu's commercially available smart glasses—Eyespeak—are capable of assisting patients who are suffering extreme mobility and communication limitations. Eyespeak has the potential to benefit a proportion of the millions of people worldwide, per year, who have stroke/traumatic brain injury-related dysarthria and associated conditions. Based on the initial ESA study, LusoSpace has also developed future smart glasses for the consumer market with dimensions and shapes similar to sunglasses. LusoSpace now has a partnership with DHL Portugal for implementing augmented reality in logistics. To date, LusoSpace has applied for three patents (one granted, to date) for augmented reality technology.

Preventing Bone Loss

The common problem of bone loss in the elderly is also observed in astronauts when they are in space. Ongoing studies on the International Space Station (ISS) indicate a reduction in bone loss and renal stone risk through use of a bisphosphonate and exercise to increase bone load and muscle training, and in a well-balanced, low-sodium diet. Improved scanning technologies are under development to promote the health of the elderly at risk of osteoporosis by providing a reference technique to enable the early detection of osteoporosis, and by creating more effective countermeasures to its effects.

Preventing Bone Loss in Spaceflight with Prophylactic use of Bisphosphonate: Health Promotion of the Elderly by Space Medicine Technologies

Bone loss and kidney stones are well-known as essential problems for astronauts to overcome during extended stays in space. Crew members engage in physical exercise for 2.5 hours a day, six times a week (15 hours a week) while in orbit to avoid these issues. Nevertheless, the risks of these problems occurring cannot be completely eliminated through physical exercise alone.

Bone plays an important role as a structure that supports the body and stores calcium. It retains fracture resistance by remodeling through a balance of bone resorption and formation. Because of reduced loading stimuli in the microgravity environment, increased bone resorption occurs, and no change in—or possibly decreased bone formation—is experienced, thereby leading to bone mass loss at a rate of about 10 times that of osteoporosis.

The proximal femoral bone loses 1% to 1.5% of its mass per month, or roughly 6% to 10% over a 6-month stay in space, with the recovery after returning to Earth taking at least 3 or 4 years.

The calcium balance (i.e., the difference between intake and excretion), which is about zero on Earth, decreases to about -250 mg per day during flight—a value that increases the risk of kidney stones.

JAXA astronaut Soichi Noguchi performs exercise aboard the ISS.

Image credit: JAXA/NASA

Bone loss and kidney stones are well-known as essential problems for astronauts to overcome during extended stays in space.

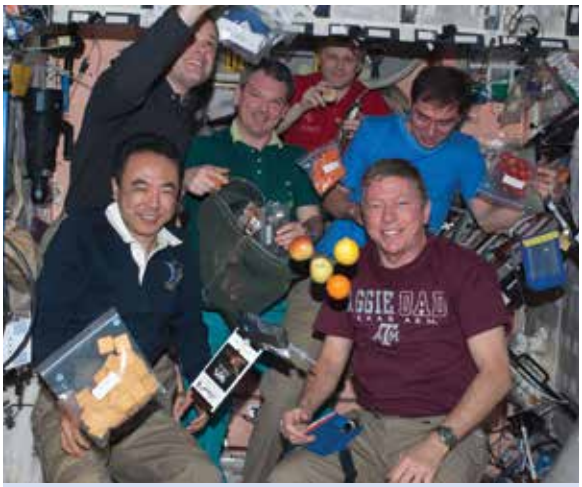
Bisphosphonate is a therapeutic agent that has been used to treat osteoporosis patients for more than a decade, with a proven efficacy to increase bone mass and decrease the occurrence of bone fracture. Through 90-day bed rest research on Earth, we confirmed that this agent has a preventive effect on the loss of bone mass. Based on these results as well as studies conducted by others, Japan Aerospace

Exploration Agency (JAXA) and NASA decided to collaborate on a space biomedical experiment to prevent bone loss during spaceflight. Dr. Adrain Leblanc of United Space Research Association and Dr. Toshio Matsumoto of Tokushima University are the two principal investigators of this study.

JAXA and NASA crew members are participating in this study by taking this agent once a week while in space. The study is still ongoing; however, early results suggest that astronauts can significantly reduce the risk of bone loss and renal stones with the combination of resistive exercise and an antiresorptive such as a bisphosphonate.

Bone loss is also observed in bedridden older people. Elderly people lose 1% to 2% per year of their bone mass because of aging and a decline in the amount of female hormone. Osteoporosis is declared when a person has a bone mass 30% lower than the average for young adults, which is a condition affecting 13 million Japanese, and one in two women aged 70 years and older. Every year, 160 thousand patients undergo operations for femoral neck fractures in Japan, followed by intense rehabilitation for 3 months. Such operations cost 1.5 million yen per person, and the total annual expense for medical treatments and care of these bone fractures amounts to 66.57 billion yen in total national cost.

The three key elements for promoting the health of elderly people to prevent fractures are nutrition, exercise and medicine. Meals should be nutritionally balanced with calcium-rich foods (e.g., milk, small fish, etc.) and vitamin D (e.g., fish, mushrooms, etc.). Limited sunbathing is also important for activation of vitamin D. Physical exercise to increase bone load and muscle training should also be integrated into each person's daily life. Those at high risk for fractures should take effective medicines to reduce the risk of fractures.



Astronauts enjoy meals aboard the ISS.
Image credit: JAXA/NASA

Accordingly, the secrets of the promotion of astronauts' health obtained from space medicine are expected to be utilized to promote the health of elderly people and the education of children.

Improved Scanning Technologies and Insights into Osteoporosis

Studying what happens during long stays in space offers a good insight into conditions such as osteoporosis. European Space Agency (ESA)-supported research on the ISS has helped in the development of high-resolution scanners that analyze bone and joint diseases in only 3 minutes.

Bone loss and its recovery is a major concern not only for astronauts, but also for people on Earth during aging and immobilization. A better understanding of the calcium loss and changing skeletal structure is crucial for the thousands of patients suffering from bone diseases or fractures.

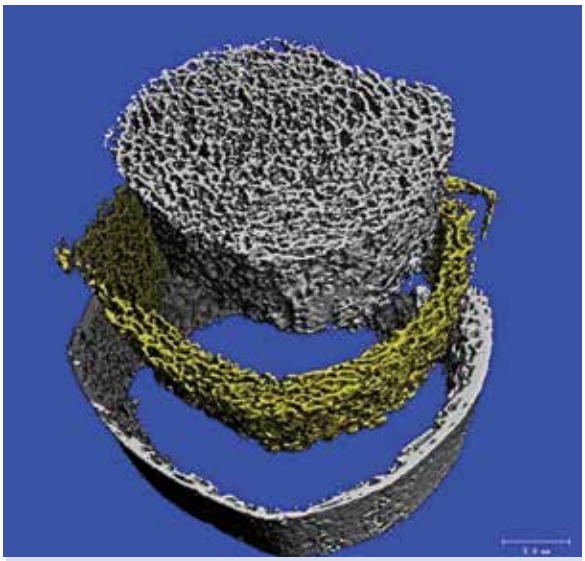
ESA's Early Detection of Osteoporosis in Space (EDOS) experiment has been testing skeletal adaptation to long-term space exposure by using three-dimensional (3-D) peripheral quantitative computed tomography (3DpQCT) as a technique for detection of bone structure. It has been providing a detailed evaluation of the bone loss and of kinetics of recovery after flight. ESA supported the development of the enhanced 3-D scanner by the Institute for Biomedical Engineering in Zürich and Scanco Medical as part of ESA's

European Space Agency (ESA)-supported research on the ISS has helped in the development of high-resolution scanners that analyze bone and joint diseases in only 3 minutes.

Microgravity Applications Programme (MAP). The scanner is providing high-quality, 3-D images of living bone structures as part of this ground experiment. This is backed up by analysis of bone biochemical markers in blood samples.

One important element that has derived from this research into bone loss in space is the successful commercialization of the 3DpQCT scanner, of which ESA supported the development, for a non-invasive/in vivo technique for observation of bone structure.

The EDOS project has been assessing the efficiency of such a technique and will contribute to the development of a reference technique to perform an early detection of osteoporosis on Earth in a unique way. These improved diagnostics in the early stages of such a medical condition may prove extremely important in the development of more effective countermeasures to the effects of osteoporosis. In 2006, 8.9 million fractures were estimated worldwide, according to the International Osteoporosis Foundation. Furthermore, interesting results have been published from the EDOS experiment in the Journal of Bone and Mineral Research, thus providing new insights into astronaut post-flight bone recovery that will feed into the development of new inflight and postflight countermeasure protocols. The project is continuing within the EDOS-2 project.



Xtreme CT distal radius.
Image credit: SCANCO Medical

The scanner (Xtreme CT, Scanco Medical) is commercially available and is used in bone research laboratories all over the world. The majority of these HR-pQCT scanners are used for research; however, their use as a diagnostic tool for doctors has increased since the introduction of the scanner in 2005. A faster version with higher resolution called Xtreme CT II is also now available.

Add Salt? Astronauts' Bones Say Please Don't.

Osteoporosis is a harsh disease that reduces the quality of life for millions. In the European Union in 2010 alone, the treatment cost of osteoporosis, including pharmacological intervention, was estimated at €37 billion, with additional costs to society estimated to bring this total up to €98 billion. This is set to rise to more than €120 billion in 2025. Osteoporosis typically affects the elderly; therefore, the rise in life expectancy in developed countries means the problems inflicted by osteoporosis are increasing. Fortunately, research done in space may change the game. Astronauts on the ISS experience accelerated osteoporosis because of weightlessness; however, it is carefully controlled, and they can regain bone mass in time once they are back on Earth.

Studying what happens during long spaceflights offers a good insight into the process of osteoporosis—losing calcium and changing bone structure—and helps to develop methods to combat the disease.

It has been known since the 1990s that the human body holds on to sodium, without the corresponding water retention, during long stays in space. However, textbooks indicated this was not possible. "Sodium retention in space" became an important subject to study.

Studying what happens during long spaceflights offers a good insight into the process of osteoporosis—losing calcium and changing bone structure—and helps to develop methods to combat the disease.

Salt intake was investigated in a series of studies—in ground-based simulations and in space—and it was found that not only is sodium retained (probably in the skin), but it also affects the acid balance of the body and bone metabolism. Therefore, high salt intake increases acidity in the body, which can accelerate bone loss.

The European Space Agency's (ESA's) SOdium LOad in microgravity (SOLO) study zoomed in on this question. Nine crew members followed low- and high-salt diets during their long-duration missions. The expected results may show that additional negative effects can be avoided either by reducing sodium intake or by using a simple alkalizing agent like bicarbonate to counter the acid imbalance.

This space research directly benefits everybody on Earth who is prone to osteoporosis.

European Space Agence (ESA) astronaut André Kuipers (left) and Russian cosmonaut Oleg Kononenko (right) with food items on the International Space Station in December 2011. In the SOdium LOad in microgravity experiment, astronaut subjects undergo two different diet regimes to determine the physiological effects of sodium on the body.

Image credit: ESA

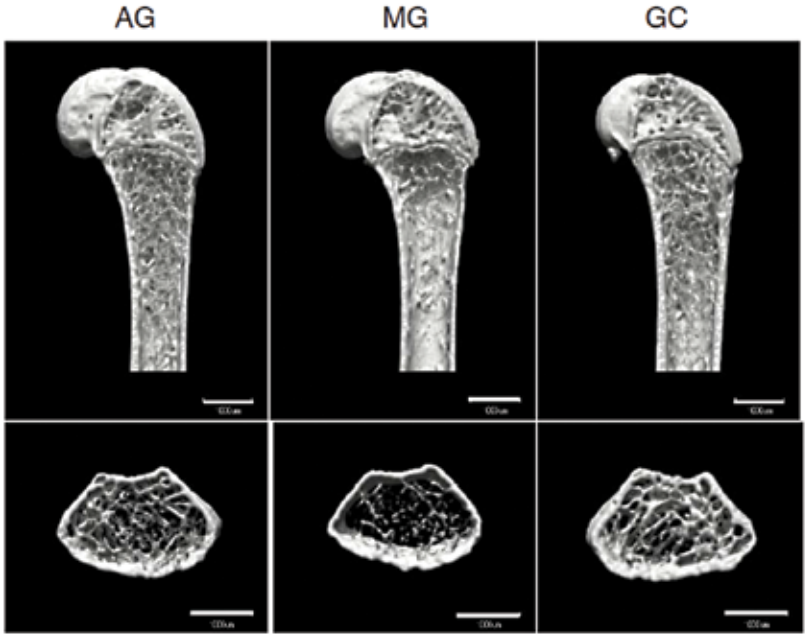
Interdisciplinary Approach to Human Health: Preventing Bone Loss in Space Helps Health Promotion of the Elderly on Earth

Along with human research on the ISS, long-term experiments involving mammals in a microgravity environment may inspire a novel insight into developing medical technologies to maintain sound health and fitness to prevent bone loss in elderly people on Earth.

Space studies using mice have shown that these animals experience physiological changes similar to those in humans. The changes are accelerated in space. If an astronaut does not exercise sufficiently in space, he or she loses bone density around tenfold faster than does an osteoporosis patient on Earth. Calf muscle loss per day in space is equivalent to the loss in 2 days for a bedridden patient and 6 months for the elderly on Earth.

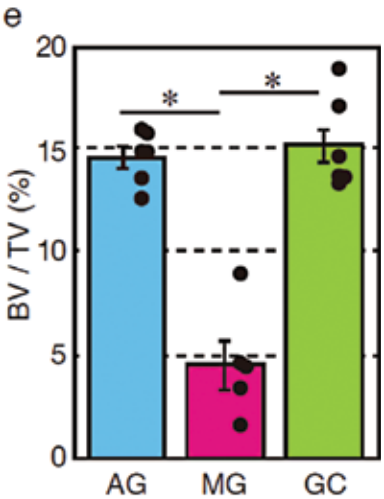
The primary goal in the Mouse Epigenetics, one of the JAXA Mouse Habitat missions, is to study altered gene expression patterns in the organs of male mice that spend 1 month in space, as well as changes in the DNA of their offspring. This study reports on the effects of artificial gravity from the on-orbit centrifuge on maintaining muscle and bone health of the ISS mice. Over an ISS duration of 35 days, mice that underwent artificial gravity exposure via regular continuous centrifugation at a 1-g (Earth-simulated) level did not display a significant decrease in soleus and gastrocnemius muscle weight and bone loss, unlike mice on the ISS that received no centrifugation. These findings provide results that will contribute to an understanding of physiological changes associated with artificial gravity exposure when

Space studies using mice have shown that these animals experience physiological changes similar to those in humans.



The representative vertical (upper) and horizontal (lower) sectional microCT photos of the proximal region of the femur. Scale bars = 1 mm. AG: Artificial Gravity, MG: Microgravity, and GC: Ground Control.

Image credit: Shiba et al, Scientific Reports, 2017.



The calculated cancellous bone volume/tissue volume (BV/TV, %) of the femurs of AG, MG and GC mice.

Image credit: Shiba et al, Scientific Reports, 2017.

considering it as a potential tool for maintaining human health for long-duration spaceflight.

Recently, locomotive syndrome, which involves the weakening of bones, muscles and other organs related to movement, has become an area of increasing interest. Through JAXA Mouse Habitat missions on Kibo, we will be able to identify factors for early diagnosis of such age-related diseases and perform pre-clinical studies to investigate the efficacy and safety of prophylactic and therapeutic drug candidates. Since aging phenomena occur 10 to 30 times faster in space than those observed on Earth, whole-body effects in such an environment can be observed without unnatural conditions such as altered genetics or partial paralysis. After a mouse returns from long-term spaceflight to Earth, it is also possible to observe its recovery from symptoms that are very much like aging. These conditions are difficult to reproduce on Earth and can be used to investigate effects on bone mass, muscle strength, immune suppression and others that are similar to age-related symptoms.

Mouse studies on the ISS provide an accelerated platform for research on aging. In upcoming years, JAXA Mouse Habitat missions will aim at developing and verifying bioinfomatics to discover scientific technologies for early disease detection, and will lead to the discovery of innovative preventive and therapeutic drugs.

Immune Defenses

Virtually the entire population is infected with one of eight herpes viruses, four of which reactivate and appear in body fluids in response to the stress of spaceflight. A patent-pending device designed for use in either a doctor's office or on a spacecraft allow for the rapid detection of one of these viruses (VZV), which can lead to earlier treatment and prevent the onset of painful shingles. Microgravity studies on the International Space Station (ISS) help researchers pinpoint genetic triggers for immune responses in T-cells, thus leading to future medical treatments on Earth for immunosuppression. Determining the changes that occur to the immune system in space provides the means to develop targeted countermeasures to adverse effects in space, as well as furnishes additional information for targeted treatments on Earth for the development of pharmaceuticals that can suppress immune response to help manage autoimmune diseases or organ transplants.

Tackling Immune System Dysfunction—from Multiple Angles

Getting sick is no fun for anyone, but it especially taxes crew members aboard the ISS. Protecting crew health is important as NASA prepares for long-duration, deep-space missions. The human immune system is a complex web of biological structures and processes; decreased activity in one piece of it can change overall disease risk. Studies have shown microgravity causes modifications in the human immune system. Figuring out why and how this occurs could help not only astronauts, but people affected by immune dysfunction here on Earth.

Many investigations aboard the space station have studied the effect of microgravity on immune system health. For example, the Functional Immune investigation analyzes blood and saliva samples to identify changes taking place in crew members' immune systems during flight, and compares the data with self-reported health information. This unique look at subtle changes in the immune system that may occur before symptoms show up, whether in space or on the ground, may help scientists pinpoint the onset of illness so they can suggest monitoring strategies or treatments to boost the immune system—and prevent full-blown infections and diseases.

Studies have shown microgravity causes modifications in the human immune system. Figuring out why and how this occurs could help not only astronauts, but people affected by immune dysfunction here on Earth.

T-cells, a type of white blood cell, play a role in activating the body's immune system. The T-Cell Activation in Aging investigation sent T-cells to the space station, then analyzed changes in their gene response back on the ground to help determine what causes depression of the human immune system in microgravity. Results support the development of better protective measures to keep crews healthy during long space missions, especially those beyond Earth orbit, well out of the reach of major medical facilities. Better understanding of immune system activation and suppression also supports improved treatment for autoimmune diseases such as arthritis and diabetes, and the natural decline of the immune system as people age.

Another investigation, Integrated Immune, tested a strategy to measure white blood cell count and stress hormones in crew members during spaceflight onboard the space station. Researchers found increases in red blood cell count, mean corpuscular volume, hemoglobin, and platelet concentration on long-duration flights. This suggests that reports of reduction in these blood elements represent early adaptation to microgravity, and that spending more time in space may somewhat compensate for those reductions. The monitoring techniques of this investigation have potential benefit in infection epidemics and remote locations on Earth, as well.

Multi-Omics evaluates how the space environment and prebiotics affect immune function. This investigation

combines data obtained from measuring changes in the gut microbiological composition, metabolites profiles, and the immune system. Recent studies indicate that imbalance in gut microbiota composition results from a variety of environmental stresses and could lead to immune dysfunction. This meta-analysis of the gut microbiota from crew members should result in better understanding of any immune dysfunction they experience. The investigation may identify potential bacterial or metabolic biomarkers for immune dysfunction, which could help the development of a method to restore gut microbiota imbalance and, in turn, immune system function.

Microbiome examines the individual microbiome, or the collection of microbes living in and on the human body at any given time. Researchers use periodic samples taken from different parts of the body and the space station to monitor crew member microbiomes and immune system function, and their interaction with the unique space station environment. The data enable assessment of the likelihood and consequences of alterations in the microbiome due to extreme environments, and the related human health risks. In addition to potentially lowering health risks during future space explorations, this study could benefit people who live and work in extreme environments on Earth. Results also could advance research in preliminary detection of diseases, alterations in metabolic function, and immune system deficiency.

Rodents such as mice and rats are "model organisms" whose characteristics make them easy to maintain, reproduce and study in the laboratory. Every model organism has been widely studied, and each has a well-documented and well-understood genetic makeup. Results from research on one model organism would likely be much the same if conducted on another similar organism. Model organisms tend to be plentiful and inexpensive, have short generation times (i.e., produce offspring in a short time), and grow relatively quickly. They are generally less complex than organisms for which they serve as the stand-in, thus making it easier to examine the research problem in question. Model organisms are essential for much research on human health, which would be impractical or unethical to conduct with human subjects

The underlying mechanisms behind immune dysfunction caused by living in space are not well understood. These and other investigations aim to figure out those mechanisms and use that understanding to help people stay healthy—in space and on the ground.

Early Detection of Immune Changes Prevents Painful Shingles in Astronauts and in Earthbound Patients

The physiological, emotional and psychological stress associated with spaceflight can result in decreased immunity that reactivates the virus that causes shingles, a disease punctuated by painful skin lesions. NASA developed a technology that can detect immune changes early enough to begin treatment before painful lesions appear in astronauts and in people here on Earth. This early detection and treatment will reduce the duration of the disease and the incidence of long-term consequences.

Spaceflight alters some elements of the human immune system. Innate immunity—an early line of defense against infectious agents—and specific components of cellular immunity are decreased in astronauts.

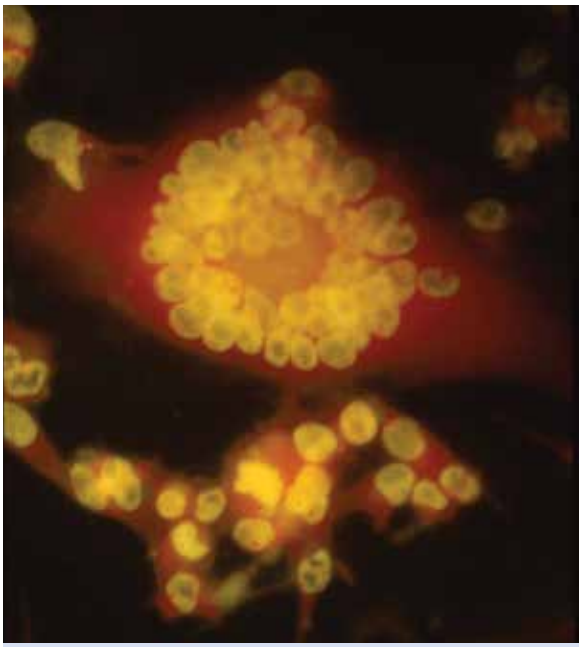
Astronauts do not experience increased incidence or severity of infectious disease during short-duration spaceflight; however, NASA scientists are concerned about how the immune system will function over the long stays in space that may be required for exploration missions.

To determine specific causes of decreased immunity in healthy individuals is difficult, but the herpes viruses have become valuable tools in early detection of changes in the immune system, based largely on the astronaut studies. Eight herpes viruses may reside in the human body, and virtually all of us are infected by one or more of these viruses. Herpes viruses cause diseases including common "fever blisters" (herpes simplex virus [HSV]), infectious mononucleosis (Epstein-Barr virus [EBV]), chickenpox and shingles (varicella zoster virus [VZV]). In immune-suppressed individuals, herpes viruses may cause several types of cancer, such as carcinoma, lymphoproliferative disease and others.

These studies demonstrate the potential value of bringing to the public a technology that could prevent a painful and debilitating condition in up to one million people each year in the United States alone.

According to the Centers for Disease Control and Prevention, one million cases of shingles occur yearly in the United States, and 100,000 to 200,000 of these cases develop into a particularly painful and sometimes debilitating condition known as post-herpetic neuralgia, which can last for months or years. The other seven herpes viruses also exist in an inactive state in different body tissues much like VZV, and similarly they may reactivate and cause disease during periods of decreased immunity.

The most common cause of decreasing immunity is age; however, chronic stress also results in decreased immunity, and an increased risk of the secondary disease, such as VZV-driven shingles. Chemotherapy, organ transplants and infectious diseases, such as human immunodeficiency virus (HIV), also result in decreased immunity. Thus, viral reactivation has been identified as an important indicator of clinically relevant immune changes. Studies of immune-compromised individuals indicate that these patients shed EBV in saliva at rates 90-fold higher than found in healthy individuals.



Varicella zoster-infected MeWo cells showing typical herpes virus-induced, multinucleated giant cells. Cultures are stained with acrydine orange to identify RNA (red) in the cytoplasm.

Image credit: NASA

The herpes viruses are already present in astronauts, as they are in at least 95 percent of the general adult population worldwide. Therefore, measuring the appearance of herpes viruses in astronaut body fluids is critical. It is widely believed that various stressors associated with spaceflight are responsible for the observed decreased immunity. Researchers at NASA's Johnson Space Center found that four human herpes viruses reactivate and appear in body fluids in response to spaceflight. Due to the reduced cellular immunity, the viruses can emerge from their latent state into active infectious agents. The multiplying viruses are released into saliva, urine or blood, and they can be detected and quantified by a method called polymerase chain reaction (PCR) for each specific virus. The finding of VZV in the saliva of astronauts was the first report of VZV being reactivated and shed in asymptomatic individuals, thus posing a risk of disease in uninfected individuals. However, the PCR assay requires large, complex equipment, which is not practical for spaceflight.

To overcome this obstacle, NASA developed a rapid method of detection of VZV in body fluids, and a patent application is currently pending. The new technology requires a small sample of saliva, which is mixed with specialized reagents that produce a red color only when VZV is present. This technology makes possible early detection, before the appearance of skin lesions. Early detection allows for early administration of antiviral therapy and thus limits nerve damage and prevents overt disease. The device is designed for use in doctors' offices or spacecraft and can be modified easily for use with other viruses in saliva, urine, blood and spinal fluid. The sensitivity and specificity emanates from an antibody-antigen reaction.

In another collaborative study, NASA and University of Colorado Health Science Center (Denver) researchers developed a tool that assessed stress hormones during space shuttle missions. Saliva samples were collected on individual filter paper strips and tested once back on Earth. The test measured cortisol and dehydroepiandrosterone (DHEA)—two important stress and immune regulatory hormones. The filter paper also can be used for proteins and other molecules of interest in saliva. Booklets of these filter papers now are being used in university and government laboratories for remote saliva collection. These studies demonstrate the potential value of bringing to the public a technology that could prevent a painful and debilitating condition in up to one million people each year in the United States alone.

With Latent Viruses, the Best Defense is a Strong Offense

Latent Virus determined that inactive viruses reactivate inside the human body during long-duration spaceflight, potentially leading to illness in crew members. Early detection of latent viruses allows crew members to employ countermeasures that boost immune response to avoid illness during exploration missions.

Monitoring and Understanding Astronaut Immune Systems in Spaceflight

Results of European Space Agency (ESA)-supported research have uncovered a quite surprising reaction of cells to exposure to weightlessness, as well as demonstrated a device for monitoring immune system behavior during long-duration exploration missions where no viable chance of sample return for analysis is possible. In 2015, the TripleLux-A experiment, which examined specific aspects of immune system function in space, was successfully performed on the ISS. This experiment studied immune response in vertebrate organisms; specifically, an immune system mechanism whereby certain white blood cells engulf and destroy "intruders" with a burst of reactive oxygen—a process called phagocytosis.

Immune response was stimulated in the cell cultures, and a photon multiplier/photon counter was used to determine the quantity of the immune response (as the cell cultures were mixed with a chemical that caused a luminescent glow in the presence of oxygen). This allowed, for the very first time, the direct measurement of a cellular function in real time on orbit and thus time-relative progression of space adaptation.

Based on real-time readings from the ISS, University of Zurich scientists were able to confirm that the mammalian cells studied are able to respond to changes in gravitational conditions extremely quickly and thereafter continue to function. Although the immune defense collapsed as soon as zero gravity hit, the defense cells made a full recovery within 42 seconds. But how do the cells adapt? Gravity has been an ever-present factor that has influenced life since life started on our planet, so how would these mechanisms exist? Weightlessness was not a factor influencing evolution on Earth. Therefore, the results raise more questions regarding the robustness of life and its astonishing adaptability, and there is hope that human cells are able to cope much better with zero gravity than we previously thought. Of course, this also promotes a further scope of inquiry that crosses over into astrobiology: Could the rapid adaptation observed be an indication that such mechanisms did not, in fact, evolve on Earth, but could have potentially been imported?

This research opens new avenues for exploring the adaptation of mammalian cells to gravitational changes. This important research could help scientists develop ways to manage or prevent changes in immune system function, both in space and on Earth, through such areas as pharmaceutical intervention, especially in light of future long-duration human exploration missions outside of low-Earth orbit. Since RhoGTPases (i.e.,a family of signaling proteins involved in a host of cell functions) are interesting candidates to explain the rapid adaptation of the oxidative burst reaction in weightlessness, these molecules should be considered as targets for countermeasures against weightless-related cellular dysfunction. However, dynamic monitoring of molecular activities in real weightlessness is of crucial importance, and appropriate experiments with real-time measurements onboard the ISS will be the key to understand the molecular dynamics of cellular adaptation to weightlessness in the future. In addition, and linked to this, the bioluminescence light measurement device could potentially be adapted into a tool for monitoring astronauts' immune systems during long-duration spaceflights. The TripleLux investigations also acted as an opportunity to test this device.

This research opens new avenues for exploring the adaptation of mammalian cells to gravitational changes.

Space Station Immunology Insights for Earth and Space

When people get sick, their immune systems kick into gear to tell their bodies how to heal. T-cells—white blood cells that act like tiny generals—order an army of immune cells to organize and attack the enemy. Microgravity studies aboard ISS are helping researchers pinpoint what drives these responses, thereby leading to future medical treatments on Earth.

Scientists have known since the early days of human spaceflight that living in microgravity suppresses the immune system. During the Apollo Program, for instance, 15 of the 29 astronauts developed an infection either during or right after flight. Forty years later, Leukin results show that immunosuppression begins within the first 60 hours of flight.

Findings from this investigation, led by Millie Hughes-Fulford, Ph.D.—a former NASA astronaut and director of the Laboratory of Cell Growth at the University of California, San Francisco—enabled researchers to pinpoint some specific genetic triggers for the go/no-go of the immune system responses in the T-cells.

It was the first time scientists have been able to show that gravity is making a difference in activation of the T-cell. A healthy body depends on these T-cells to give orders for the immune system to function properly as it marches into battle. However, certain factors such as signal interruption, delayed responses or even outright cell death can hinder victory. A suppressed immune system is like an army with an ineffective leader, significantly reducing the chances of a successful fight.

Results revealed that specific genes within T-cells showed down regulation—a decrease in cell response—when exposed to microgravity. This combined down regulation in the genetics of T-cells leads to a reduction in the body's defense against infections during spaceflight in various ways. For instance, a reduced pro-inflammatory response (i.e., the cell's protective reaction to initiate healing) occurs. Cells also produce fewer cytokines, which are the proteins responsible for signaling communications between cells. A negative impact to a cell's ability to multiply, known as mitogenesis (i.e., the chromosomal splitting in a cell nucleus necessary for cell reproduction), also occurs.

Results revealed that specific genes within T-cells showed down regulation—a decrease in cell response—when exposed to microgravity.

Expedition 30 Flight Engineer Andre Kuipers, ESA, works with the Kubik facility in the Columbus Module of the ISS.

Image credit: NASA

Examples of immunosuppression on Earth include the Acquired Immune Definiciency Syndrome (AIDS)-related HIV infection, rheumatoid arthritis and even age-related impacts to the immune system, which is why the elderly have a difficult time fighting off infections such as pneumonia. Identifying how the immune system works at the cellular level provides a powerful tool to develop treatments at the root of the defense response. This is similar to a negotiation for peace talks before conflict breaks out, instead of trying to raise a white flag in the midst of an already raging battle. If doctors can isolate and control specific immune responses, they increase the chance for recovery. With the removal of gravity as its own variable, the data gathered from immune studies in space can be used to help understand some of the immune challenges seen in these populations on Earth.

Hughes-Fulford launched a follow-on immunology study aboard the space station. This study was funded by a grant from the National Institutes of Health and sponsored by the SS U.S. National Laboratory (**http://www.iss-casis.org/**). T-Cell Activation in Aging,

which launched on the SpaceX-3 commercial resupply mission, investigates another class of control points in T-cells that trigger immune response. Finding the genes that tell the cells to turn on and off is key to advancing medical options to improve immune system functions. Data analysis is underway, with the potential to pinpoint new candidate pharmaceutical targets to treat immunosuppression.

Targeted Treatments Improve Immune Response

Cell biology experiments have been uncovering different aspects of altered immune system response in weightlessness. Determining the changes that occur to the immune system in space provides the means to develop targeted countermeasures to adverse effects in space, as well as produces additional information for targeted treatments on Earth. This could be either for developing pharmaceuticals that can improve treatment and recovery from certain medical conditions, or for alternatively targeted treatments that can suppress immune response—e.g., to help deal with autoimmune diseases or organ transplants.

Research undertaken in the Kubik incubators has uncovered many altered mechanisms that occur in the immune system in space using biological samples processed at body temperature at 0 g and 1 g (centrifuge) in orbit, including the discovery of reduced function in monocyte white blood cells that is due to a disrupted cytoskeleton. This is an apparent inhibition of the Protein Kinase C family of enzymes and a specific immune cell transmitter, called the Rel/NF-κB pathway, which stops working in weightlessness. All of these are important mechanisms in immune response.

Determining the changes that occur to the immune system in space provides the means to develop targeted countermeasures to adverse effects in space, as well as produces additional information for targeted treatments on Earth.

ESA astronaut Thomas Reiter undertakes in-orbit activities for one of ESA's immunology experiments in 2006.

Image credit: ESA

One ESA experiment in this domain—the ROle of Apoptosis in Lymphocyte Depression (ROALD) experiment series—was undertaken in 2008, with a follow-up experiment in 2011. In the first part of the experiment, researchers discovered that an enzyme called 5-LOX, which in part regulates the life expectancy of human cells, became more active in weightlessness and could play a real role in causing weakened immune systems. The 5-LOX enzyme can be blocked with existing drugs; therefore, using these findings to improve human health could be a close reality. Additional efforts to understand this treatment pathway, targeting patient treatment on Earth, is ongoing.

Genetic Markers Tell a Valuable Story about Astronaut Health

The ROle of Apoptosis in Lymphocyte Depression—or ROALD—experiment examined the immune dysfunction experienced by crew members during space missions, and revealed new genetic markers to monitor the health status of future long-duration space explorers to ensure their ability to successfully complete objectives on missions beyond low-Earth orbit.

Developing New Therapies

Studying the unique and complicated structures of proteins in the human body leads to the development of medical treatments. Microgravity allows unique conditions for growth of protein crystals where no gravity or convection is present to disrupt their growth. The protein expressed in certain muscle fibers of patients with Duchenne Muscular Dystrophy, which affects 1 in 3,500 boys, has been successfully crystallized in space, thus revealing a new inhibitor several hundred times stronger than the prototype inhibitor.

Microencapsulation is the process by which tiny, liquid-filled, biodegradable micro-balloons are created. These balloons contain specific combinations of concentrated anti-tumor drugs. The goal is to deliver this medication using specialized needles to specific treatment sites within a cancer patient. The microgravity environment, where density differences do not cause layering of the medication, has allowed for the development of devices on Earth to create these microcapsules and devices that will aid in the drug delivery using this technology. Progress continues toward clinical studies in cancer patients one day in the future.

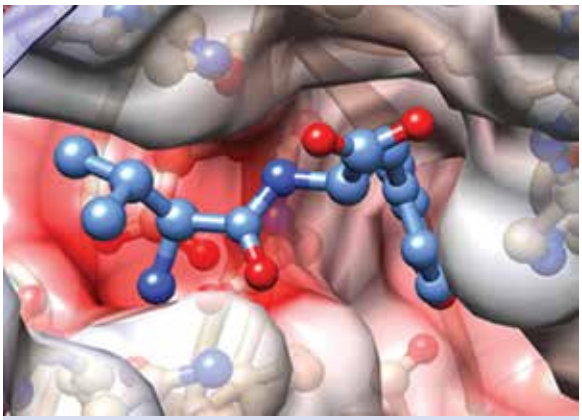
Ongoing research of gravitational unloading supported by dry immersion technology allows for a broad spectrum of possible clinical applications such as the early diagnosis of slow-developing neurological disorders, the combating of edema that responds poorly to medication, post-operative rehabilitation, sports medicine and rehabilitation for premature babies.

Getting to the Bottom of Humans' Greatest Infection: Periodontal Disease

More than 100,000 types of proteins are present in the human body. Each structure of the proteins provides important information related to our health. Through structural studies of proteins and the Japan Aerospace Exploration Agency (JAXA) High-quality Protein Crystal Growth (PCG) experiments on the International Space Station (ISS) for 15 years since 2003, the microgravity environment has been verified to offer a perfect laboratory because of its unique conditions. In microgravity, there is no convection to disrupt the liquid solution, nor is there precipitation to cause heavier molecules to sink. In such an environment, protein molecules form orderly, high-quality crystals that provide optimal structures for study. This high-quality protein crystallization allows us to find the structure of disease-causing protein to develop a new medication and effective treatment.

During a session of the JAXA PCG experiment, protein samples are equipped with the Protein Crystallization Research Facility (PCRF) inside the Japanese

More than 100,000 types of proteins are present in the human body. Each structure of the proteins provides important information related to our health.

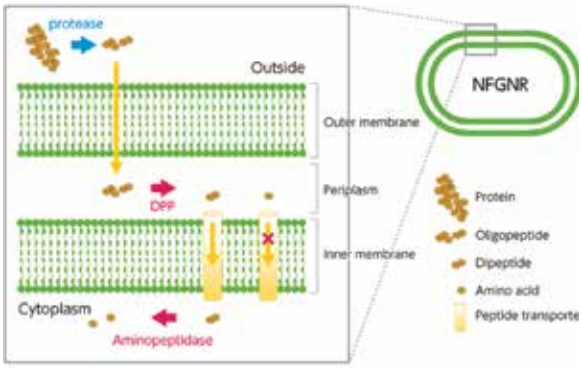


Binding of a peptide to DAP BII.
Image credit: Iwate Medical University

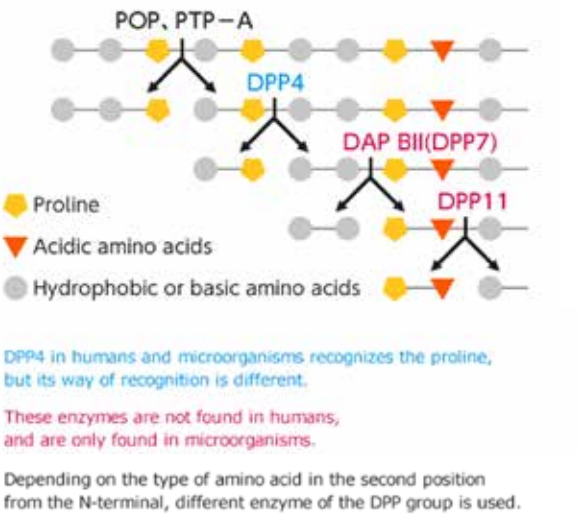
Experiment Module (JEM), where the samples are kept for a period of 1 to 2 months at a stable temperature, 20°C (68°F). A counter-diffusion method called the Gel-Tube method is used for crystallization whereby polyethylene glycol or salt solution is diffused into the protein solution, which is separated by a porous membrane inside a tube. In this method, concentration of polyethylene glycol in the protein solution gradually increases and finally satisfies the condition for protein crystallization. In addition to the existing experiments conducted at 20°C (68°F), experiments at 4°C (40°F) are now being started. Crystallization at 4°C (40°F) realizes the crystallization of candidate drugs in high demand, such as unstable hydrosoluble proteins and membrane proteins.

During the ISS PCG experiments, the crystal structure of the dipeptidyl peptidase 7 (DPP) was discovered for Antimicrobial Agent Development. Dr. Yasumitsu Sakamoto of Iwate Medical University used the microgravity environment aboard the ISS for JAXA PCG experiments. Dr. Sakamoto explains this newly discovered enzyme: In the course of the research, this enzyme, named DAP BII (DPP7), was found to be important for the proliferation and growth of a group of bacteria: Non-Fermenting Gram Negative Rods (NFGNR), which live by using peptides and proteins as their nutrients. NFGNR includes the causative bacteria of periodontal disease and hospital-acquired infection. Incidentally, periodontal disease is the most widespread infectious disease among human beings. When he started this study, he considered this enzyme to be both unusual and interesting. Then Dr. Sakamoto also considered that if a substance could inhibit the function of DAP BII (DPP7), which is essential for growth of the pathogen, and other enzymes in the DPP family, the substance would become an antimicrobial agent. Thus, the research team also decided to develop antimicrobial agents.

Several types of DPPs exist, and each one works differently. For example, DAP BII (DPP7) recognizes and cleaves hydrophobic or basic amino acids. On the other hand, DPP11 recognizes acidic amino acids. These enzymes are not found in humans, they are only found in microorganisms. In other words, if you can make medicines to suppress the function of these enzymes, it is harmless for humans and only suppresses the growth of bacteria. If the peptide binding mode of protein is clarified in detail, a new drug could be created that targets only DPP of microorganisms, but has no effect on humans.



Expected mechanism of peptide uptake of NFGNR.
Image credit: Iwate Medical University



Substrate specificity of the DPP family.
Image credit: Iwate Medical University

Following the discovery of DPP7, the researchers are keeping on analyzing the structure of DPP11 to use it as a target for antibiotics. The present analyses of DPP11 structure could be useful templates for the design of specific inhibitors of DPP11 from pathogenic organisms. In terms of application, researchers aim to develop antibacterial drugs. Scientifically, they will keep going to elucidate the entire mechanism of peptide uptake.

For more information, visit the following link:
http://iss.jaxa.jp/kiboexp/theme/first/protein/en/interview/interview02.html#main

Protein Crystal Growth in Space Shows Pathway to Duchenne's Muscular Dystrophy Treatment

On the International Space Station, Japanese scientists crystallized a human prostaglandin D2 synthase-inhibitor (H-PGDS/HQL-79 complex), which plays a critical role in the formation of Duchenne's muscular dystrophy (DMD). This allowed researchers to identify a new molecule, TAS-205, which is considerably more effective than HQL-79 at mitigating the expansion of muscle necrosis in mice and dogs. A Phase I study sponsored by the multinational Taiho Pharmaceutical Corporation verified the TAS-205 inhibitor to be safe for use in humans. Taiho Pharmaceutical has continued to sponsor research on TAS-205 and, in October 2017, completed a 24-week Phase II trial with 33 DMD patients.

Improving Treatments With Tiny Crystals

Cancer patients often receive treatments through a slow intravenous infusion that takes several hours in a doctor's office or hospital. One day, thanks to research aboard the ISS (**https://www.nasa.gov/mission_pages/station/main/index.html**), those same treatments may become as simple as a quick injection.

A team of Merck researchers led an investigation, PCG-5, seeking to grow the therapeutic monoclonal antibody Keytruda® in highly ordered, uniform crystalline form. The research aims to improve the drug purification process as well as drug formulation and delivery.

"If we can simplify the administration, it would be better for the patient and practitioner, and it would make the entire process a little easier to handle," said Matthew Truppo, executive director and head of Chemical Biotechnologies and Global Structural Sciences at Merck (https://www.merck.com/index.html).

Merck's investigation is different from previous crystal growth experiments in that it grows a crystalline suspension of millions of tiny uniform crystals.

Monoclonal antibodies make up the majority of therapeutic biologic drugs. Biologics are made from large, complex molecules derived from living organisms such as microorganisms or human or animal cells.

However, monoclonal antibodies are not very soluble, making it difficult to achieve highly concentrated formulations of drugs like Keytruda®. Producing high-quality crystalline suspensions of monoclonal antibodies would enable pharmaceutical companies to change the drug formulation and switch from intravenous administration to an injection. Besides greatly improving quality of life for patients, injections would save time and reduce costs.

The space station serves as an ideal platform for protein crystallization experiments that grow large, high-quality crystals, or crystal complexes of proteins bound to small molecules, for analysis aimed at structure-based drug design. The absence of the physical forces of gravity and decreased fluid motion in microgravity make it possible to produce more ordered, high-quality crystals that often provide higher-resolution structures.

"When you're trying to get very high quality and very uniform crystals, it's important to have a really slow and orderly process by which those molecules come together to form a crystal," Truppo said. "The more you minimize movement within the solution and rely solely on the ability of the molecules to one by one come together and build the crystal lattice, the more likely you'll get a highly ordered, pure crystal."

Microgravity allows testing of unique preparations, which answers basic science questions that can be applied to drug development on the ground and, ultimately, manufacturing. Merck researchers hope to learn more about the key variables affecting crystal growth that could then be applied to pharmaceutical applications of interest back on Earth.

The space station serves as an ideal platform for protein crystallization experiments that grow large, high-quality crystals, or crystal complexes of proteins bound to small molecules, for analysis aimed at structure-based drug design.

Protein crystal growth box.

Image credit: ISS National Laboratory

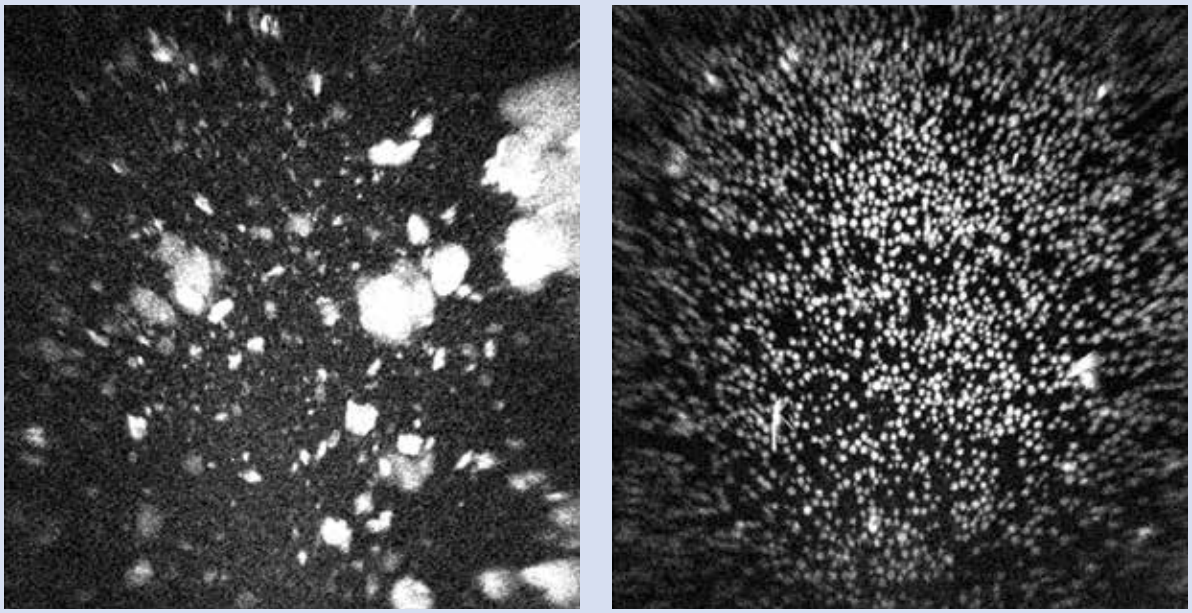
The production of high-quality crystalline suspensions of monoclonal antibodies would not only allow for improvements in drug formulation and administration, it could also lead to improvements in drug storage.

"Currently, most monoclonal antibody preparations have a limited shelf life and must be stored under refrigerated conditions in large, cumbersome bags," said Principal Investigator Paul Reichert. A concentrated drug substance stable at room temperature could be moved long distances in small containers.

Demonstrating that crystalline suspensions of monoclonal antibodies are stable, long-term, at room temperature would eliminate the need for and costs of refrigerated transportation and enable distribution of the drug in areas without refrigeration. Additionally, lowering the costs of production and transport could ultimately lead to lower costs for patients.

The investigation also could improve the drug purification process, further lowering production time and cost. The researchers sent samples of the monoclonal antibody at different steps in the purification process to the space station to see if crystals would form and what level of purity could be achieved. Preliminary analysis showed clear differences between the ground and spaceflight samples.

"The samples crystallized in microgravity contain highly ordered, uniform crystalline suspensions similar to the crystalline suspensions of alpha interferon from our previous space shuttle experiments," Reichert said. "This is exciting because it demonstrates the results are reproducible under these conditions."



Ultraviolet imaging of a ground control sample (left) and spaceflight sample (right) from Merck's investigation, clearly showing the much more uniform size and distribution of crystals grown in microgravity.

Image credit: Merck

If additional analysis shows that the space-grown crystals have the desired property parameters, researchers can apply that information to experiments on the ground.

The team's findings could help researchers better understand the crystallization process of therapeutic monoclonal antibodies in general. Such knowledge could lead to important advances in monoclonal antibody drugs that could one day translate into significant improvements in quality of life for patients with cancer and autoimmune disorders.

Using Ultrasound to Zap Kidney Stones and Other Health Problems in Space

Kidney stones, often painful and debilitating, have long been a serious concern for astronauts. Dehydration, stasis, and bone demineralization are strong contributors to kidney stones and commonly occur in microgravity. Astronauts have reported kidney stones, postflight, more than 30 times.

Technology currently under investigation could solve this and other health problems related to spaceflight. The Flexible Ultrasound System (FUS) demonstrates use of a ground-tested, software-based ultrasound technology in a device for deep-space missions. FUS aims to provide state-of-the-art clinical internal imaging and additional capabilities, such as using ultrasound for therapy as well as diagnosis, and facilitating development of algorithms for advanced image interpretation.

FUS is based on the commercial GE Vivid-E95 clinical ultrasound device. Modifications by ZIN Technologies (https://www.zin-tech.com/) incorporate advanced capabilities that allow researchers not only to detect and manipulate renal stones, but also assess bone health, enhance healing of musculoskeletal injuries, monitor intracranial pressure via eye scans, and provide training tools so astronauts can produce diagnostic-quality ultrasound scans autonomously.

> Combined with its other capabilities, the flexible ultrasound technology provides welcome relief for astronauts in space and people on the ground.

In addition to developing an integrated ultrasound imaging and therapy device, goals of this ongoing work include providing a higher degree of control over scanning parameters and greater access to raw ultrasound data to facilitate algorithm development, and developing medical ultrasound systems that function more readily with radiation-tolerant processes for deep-space missions.

One of the completed FUS investigations, Prevention of Renal Stone Complications in Space Exploration, refined capabilities previously demonstrated on human subjects on the ground to screen for, diagnose, and treat renal stones using FUS onboard the space station.

More than 40 papers have been published on this ground-based work, more than 40 patent applications submitted, and the technology licensed to a spin-off company, SonoMotion Inc (**http://www.sonomotion.com/**).

"We have shown we can produce a working prototype, develop sufficiently high-quality imaging to guide treatment, train new users, and conduct a successful clinical trial," says Principal Investigator Michael Bailey of the University of Washington. "We have implemented our technologies with different probes, and our imaging software can be added to an FUS or commercial imager. The system, once validated in flight, largely closes the gap for diagnosing and treating kidney stones on exploration missions."

Future investigations onboard the space station are scheduled to continue to refine and develop the technology for use in space.

The system also has applications on Earth. One in 11 Americans has suffered from kidney stones—more than have diabetes or cardiovascular disease. FUS technology can be used on any imager by any user to improve accuracy of stone size determination. Overestimated stone size leads to unnecessary surgeries, and underestimated stone size leads to obstructions and emergency room visits. A study funded by NASA at the University of Washington tests ultrasound-based technologies for stones in the emergency department.

Determining kidney stone size similarly determines the risk and appropriate course of action in space.

Astronauts exposed to spacefight face increased risk for renal stone formation. In addition, a potential medication used to combat spaceflight-associated neuro-ocular syndrome may also increase this risk.

This work provides ways to diagnose, treat and minimize the consequences of stones that may form while in space.

Combined with its other capabilities, the flexible ultrasound technology provides welcome relief for astronauts in space and people on the ground.

Cancer-targeted Treatments from Space Station Discoveries

Invasive and systemic cancer treatment is a necessary evil for many people with the devastating diagnosis. These patients endure therapies with ravaging side effects, including nausea, immune suppression, hair loss and even organ failure, in hopes of eradicating cancerous tissues in the body. If treatments targeted a patient's cancerous tissues, it could provide clinicians with an alternative to lessen the delivery of toxic levels of chemotherapy or radiation. Remarkably, research that began in space may soon result in such options here on Earth.

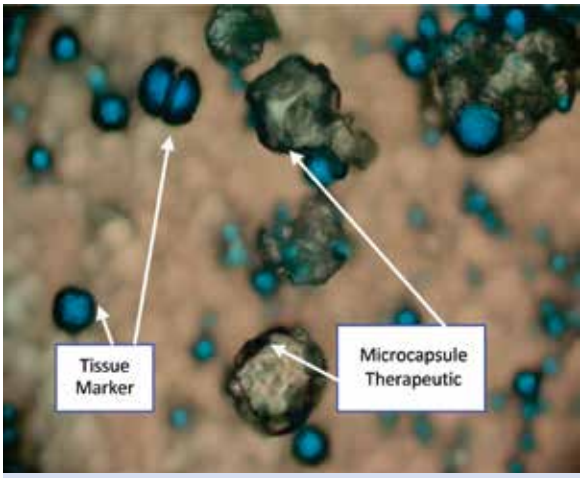
A particular series of research investigations is making further advancements in cancer therapy using the distinctive microgravity environment aboard the ISS. A process known as microencapsulation, which is being investigated aboard the space station, is able to produce tiny, liquid-filled, biodegradable micro-balloons containing specific combinations of concentrated anti-tumor drugs. Using specialized needles, doctors could deliver these micro-balloons, or microcapsules, directly to specific treatment sites within a cancer patient, effectively revolutionizing cancer treatment.

Dr. Dennis Morrison of NASA's Johnson Space Center used the microgravity environment aboard the space station for microencapsulation experiments as a tool to develop the Earth-based technology, called the Microencapsulation Electrostatic Processing System-II (MEPS-II), to make the most effective microcapsules. The technique for making these microcapsules could not be done on Earth because the different densities of the liquids would layer. However, in space, microgravity brought together two liquids incapable of mixing on Earth (80% water and 20% oil) in such a way that spontaneously caused liquid-filled microcapsules to form as spherical, tiny, liquid-filled bubbles surrounded by a thin, semipermeable outer membrane.

In space, surface tension shapes liquids into spheres. Each molecule on a liquid's surface is pulled with equal tension by its neighbors. The closely integrated molecules form into the smallest possible area, which is a sphere. In effect, the MEPS-II system allowed a combination of liquids in a bubble shape because surface tension forces took over and allowed the fluids to interface rather than sit atop one another. Studying the samples upon return to Earth allowed scientists to understand how to make a device that could create the same microcapsules on Earth.

A particular series of research investigations is making further advancements in cancer therapy using the distinctive microgravity environment aboard the ISS.

The MEPS-II system has been brought to commercial scale under the U.S. Food and Drug Administration (FDA) Good Manufacturing Practice requirements, and commercialization of the MEPS technology and methods to develop new applications for these unique microcapsules is underway. The space station research led to 13 licensed microcapsule-related patents, and two that are currently pending.



The oil contains a visualization marker that is traceable by ultrasound and CT scans to allow doctors to follow the microcapsules as they are site-specifically delivered to the tumor. The semipermeable outer skin releases the drug slowly, through its physical ability to be timed released.

Image credit: NuVue Therapeutics, Inc.

In laboratory testing, MEPS-II microcapsules containing anticancer drugs were injected directly into a human prostate and lung tumors in animal models. In follow-on tests, these models were also injected following the delivery of specific cryosurgical effects, similar to a freeze-and-thaw effect on the tumorous tissues. Injecting the microcapsules directly into the tumor demonstrated improved site-specific therapeutic results and the inhibition of tumor growth. Following cryosurgery, the microcapsules demonstrated improved destruction of the tumor better than freezing or local chemotherapy alone.

Though the previous laboratory studies of these microcapsules were primarily focused on prostate and lung cancer, NuVue Therapeutics, Inc. has been further developing the technology to target breast cancer. In May 2018, NuVue Therapeutics, Inc. will complete the pre-clinical trials necessary for FDA submission for approval of the microcapsules as innovative micromarkers—i.e., tiny markers that can be used to visualize the borders of tumors to monitor their size throughout the treatment process. The team is also currently developing plans for FDA approval of the microcapsules filled with anti-tumor drug therapies as a treatment option, along with several devices that will aid in drug delivery using this technology.

After achieving full FDA approval, planned clinical trials will involve injecting the microcapsules with the anti-tumor drugs directly into tumor sites in humans at both MD Anderson Cancer Center in Houston, Texas, and the Mayo Cancer Center in Scottsdale, Arizona.

Dennis Morrison poses with the Microencapsulation Electrostatic Processing System flight hardware that was used on the ISS to produce microcapsules for cancer treatment delivery.

Image credit: NASA

Given the success in animal models in laboratory studies with human prostate and lung tumor treatment, the NuVue team has high hopes of being able to begin use of the microcapsule treatment in breast cancer in the near future.

These kinds of technologies are enabled by the availability of the microgravity environment aboard the space station. Just as microgravity can aid in the discovery of new technologies for cancer treatment, these microcapsules may one day aid in the recovery of breast and other specific deep-tissue cancers.

Using Weightlessness to Treat Multiple Ailments

The technology of dry immersion was developed as an Earth-based model to study the effect of microgravity factors on the human body. Using this model, the effectiveness of measures developed to prevent the negative impact of spaceflight factors on people has been, and continues to, be evaluated. The countermeasures currently used on the ISS were tested in experiments involving dry immersion.

Experts at the Institute of Biomedical Problems (IBMP) developed the automated immersion system to create water hypodynamia (utility model patent #44505 “Immersion bath” and invention patent #2441713 “Polymer covering and device for dry immersion”).

The concept of the technology involves submerging a person in an immersion bath filled with water. The immersion system is an ergonomically designed tub with a built-in elevation mechanism, filtration, and temperature control systems. The subject is kept separate from the water by a thin waterproof cloth with an area significantly exceeding the area of the water’s surface. In this way, conditions closely simulating the lack of gravity are recreated. As a result,

The use of the immersion system is also a particularly valuable rehabilitation measure for premature babies who are exposed to the effects of gravity following the intrauterine environment.

changes typical of acute gravitational unloading are reproduced in the body.

The potential use of the system for health purposes relates to the specific physiological changes in the body caused by gravitational unloading. In particular, acute disruptions occur in the mechanisms of sensory interaction. These disruptions counteract compensatory processes in the central nervous system, thus resulting in discovery of latent neurological disruptions. Treatment with dry immersion is also accompanied by a number of physiological shifts, such as the redistribution of fluids in the body, which have positive effects in certain cardiovascular conditions such as edema.

The drug-free method of dry immersion offers the user the following: relaxation of muscles; increase in immunity; elimination of edema; and, normalization of blood pressure, thus making it possible to use the immersion system for the early diagnosis of slow-developing neurological disorders and to combat massive edema that responds poorly to pharmacological remedies.

The use of dry immersion may also be an effective mechanism for rehabilitative treatment in areas such as psychoneurology, traumatology, orthopedics (post-operative rehabilitation), sports medicine, clinical neurophysiology and applied psycho-physiology.

The use of the immersion system is also a particularly valuable rehabilitation measure for premature babies who are exposed to the effects of gravity following the intrauterine environment. Perinatal damage to the central nervous system (i.e., hyperexcitability; depressive, muscle hypertonia, and cephalohematoma syndromes) is an opportunity for the use of the dry immersion method. Additional uses for dry immersion include the treatment of immune disorders, hormone imbalances, muscle disease, wound healing and cardiovascular health.

The spectrum of possible applications of this system that simulates spaceflight conditions, such as those experienced by the ISS, is fairly broad and will expand with further study.

Dry immersion complex.

Image credit: Institute of Biomedical Problems, Russia

New prototype of the automated immersion system used in clinics.

Image credit: Aerospace Medical Center and Technology

Food and the Environment

Microbiology is a vitally important area, not only within human spaceflight but also for humans on Earth. Microorganisms such as bacteria, archaea, fungi and algae have a detrimental or a beneficial impact on our daily lives. This research has far-reaching effects that feed into many different areas of biotechnology as microorganisms have a role in food spoilage, waste and sewage treatment and processing, nutrient cycling and exchange, pollution control, and in increased greenhouse gases.

Studying the effects of gravity on plants led to the development of an ethylene scrubber. This technology is now used as an air purifier that destroys airborne bacteria, mold, fungi, viruses and odors.

The scrubber is used for food preservation in major supermarkets, high-end refrigerator technology, and trucks that carry groceries to remote regions of countries such as India, Saudi Arabia and Kuwait, to name a few. Even the health care industry benefits from the use of these units in clinics, operating rooms, neonatal wards and waiting rooms, thereby making these locations safer for their inhabitants.

Plant research in a space greenhouse has permitted the study of root zone substrates in space, thereby allowing scientists to improve predictions of how artificial soils will behave when irrigated both in space and on Earth in experimental forests.

Microbiology Applications from Fungal Research in Space

Microorganisms have both negative and beneficial effects. Different species of fungi are inherent in many of these processes, and can do the following:

- Spoil food, but assist in waste and sewage treatment and processing as well as nutrient cycling and exchange.
- Assist in pollution control but also increase greenhouse gases.
- Cause disease but can be used in the manufacture of antibiotics, detergents and pesticides.
- Cause deterioration in manufactured materials and buildings but can also be used in the recovery of metals in the mining sector as well as the production of biofuels and fertilizers.
- Provide insight into one species, which may provide insights into others and hence feed into different applications.

The Growth and Survival of Coloured Fungi in Space-A (CFS-A) experiment determined the changes that weightlessness and cosmic radiation have on the growth and survival of various coloured fungi species. Understanding any changes in the physiology and survivability of different microorganisms in space can help determine the effect that this may have on spacecraft, on associated systems and supplies, and on the astronauts who inhabit them. This could provide important insights for developing countermeasures to possibly deleterious microorganisms, help to draw conclusions on how the space environment may affect similar organisms, and feed into biotechnology applications in the future.

The main fungal species studied in the CFS-A experiment was Ulocladium chartarum, which is well known to be involved in biodeterioration of organic and inorganic materials and suspected to be a possible contaminant in spacecraft. Other species studied were: Aspergillus niger (which causes a disease called black mold on certain fruits and vegetables, and commercially accounts for 99% of global commercial citric acid production); Cladosporium herbarum (frequently the most prominent mold spore in air and found on dead herbaceous and woody plants, textiles, rubber, paper and foodstuffs of all kinds); and Basipetospora halophile (which survives in high-saline environments).

As we gain knowledge of the life histories of key species of fungi in the space environment, that knowledge can be readily applied to better manage these species on Earth.

Flight day 5 sample from the Coloured Fungi in Space experiment.

Image credit: CFS-A science team

The CFS-A experiment clearly indicated that Ulocladium chartarum is able to grow under spaceflight conditions, thereby elaborating a new strategy to survive for a short time by developing submerged mycelium, and for a long time by developing sporulating microcolonies on the surface of the nutrient source on which it was cultured. In spacecraft, U. chartarum and other fungal species could find a favorable environment in which to grow invasively, unnoticed, in the depth of surfaces under the right conditions, thus posing a risk factor for biodegradation of structural components as well as a direct threat for crew health. This will be especially important for future long-duration missions outside of low-Earth orbit where astronauts will have to be more self-sufficient in maintaining spacecraft and systems. Furthermore, some food supplies would need to be preserved for longer than potentially 18 months. However, along the same line, this kind of research could potentially feed into strategies for waste recycling on spacecraft and the development of biological life support systems in the future. As we gain knowledge of the life histories of key species of fungi in the space environment, that knowledge can be readily applied to better manage these species on Earth.

Experiments with Higher Plants on the Russian Segment of the International Space Station

Some of the most important tasks in space biology include creating reliable and effectively functioning life support systems, and providing sustaining food sources for crew members. For long-term interplanetary spaceflights and planetary bases, the human life support system and food production must be based on regenerating the living environment from life support products through physical/chemical and biological processes. Greenhouses will most likely be designed for the cultivation of vegetables—primarily greens and herbs. However, to implement these plans, plants must grow, develop and reproduce in spaceflight with cultivation productivity similar to how it is done on Earth. To address this need, a series of 17 Rasteniya experiments were conducted from 2002-2011 using the Lada greenhouse on the Russian Segment of the ISS.

For the first time in space research, four consecutive generations of genetically tagged pea line seeds were obtained in spaceflight.

Multigenerational studies were carried out to culture genetically tagged dwarf pea plants in the Lada space greenhouse. For the first time in space research, four consecutive generations of genetically tagged pea line seeds were obtained in spaceflight. The growth and development characteristics of various lines of pea plants did not change in a significant way compared to ground-control samples. Using molecular methods with random amplified polymorphic DNA (RAPD) primers with 10 markers and analyzing chromosomal aberrations, it was demonstrated that plants having undergone four complete development cycles in spaceflight did not manifest genetic polymorphism, which makes it possible to assert that there is no impact of spaceflight factors on the genetic apparatus of plants in the first to the fourth “space” generations.

To prepare a chain of higher plants for future life support systems of space crews, experiments were carried out to cultivate the leafy vegetable plant Mizuna (Brassica rapa var. nipposinica). Results showed that the significant increase in the parameter of total contamination of ISS air did not result in a decrease in productivity of the leafy vegetable plant; however, the plants responded with a change in gene expression.

A space experiment to grow super dwarf wheat during a complete vegetation cycle showed that the rate of plant development over 90 days did not differ from data

from ground-control experiments. When the space-produced seeds were planted on the ground, plants that grew were no different from the control sample.

The completed work has great applied value because, in the process of creating and operating the space greenhouse, cutting-edge equipment and software were developed, thereby making it possible to grow plants automatically. The psycho-physiological aspect of the interaction between humans and plants in a habitable pressurized volume was studied, and data were obtained on the safety of cultivating plant biomass on a space station for human consumption. These data are of great interest for design work to create productive greenhouses that are part of promising life support systems of any living complexes that are cut off from the Earth's biosphere.

Scientists have also studied the interaction of plants with the soil. The processes by which plant roots receive water, gases and nutrients are different in space than they are on Earth. On Earth, gravity and surface tension combine to move water through soil, thus allowing air to move through the pore spaces in the soil to the plant's roots. In space, soil is replaced with an artificial growth medium that is made up of small grains or other porous material. In microgravity, liquid moves through capillary action, where the liquid is attracted to the adjacent surface of a solid material. The surface tension of the liquid pulls additional liquid along as each new surface is wetted. If the plant is overwatered and all of the surface area and open spaces within the growth medium are filled with liquid, then gas (air) cannot move, and the plant's roots are deprived of air and oxygen. When properly wetted, as water is used by the roots, surface tension pulls additional liquid along without filling the pore spaces, and therefore without preventing oxygen from diffusing through the open spaces to the roots. Studies in the Lada greenhouse have addressed the importance of root zone media in these extreme artificial conditions. Scientists have studied a variety of root zone substrates—growth media, material particle sizes and packing structure—and learned which combinations work best.

Knowledge of root zone substrates has allowed scientists to improve their predictions of how artificial soils will behave when they are irrigated—in space and on Earth—and to design specific plant growth media and artificial soils for greenhouses and other large-scale plant production facilities on Earth. Models that describe the behavior of water and oxygen learned from these space experiments have been published in scientific journals, thereby allowing commercial users to access the information without divulging their propriety growth media mixtures. Sensor technology developed to monitor the Lada root zone is being applied to monitor soil properties in a state-of-the-art measurement facility at an experimental forest.

Colleagues from many Russian and non-Russian organizations participated in carrying out work according to the Rasteniya program in the Lada

Cosmonaut Sergey Volkov (onboard engineer Expeditions 28/29) studies super dwarf wheat as part of the Rasenyia-2 investigation.

Image credit: NASA

Cosmonaut Maxim Suraev, Expedition 22 flight engineer, holds Mizun lettuce plants from the BIO-5 Rasteniya-2 (Plants-2) experiment in the Service Module during Expedition 20.

Image credit: NASA

greenhouse on the ISS Russian Segment. The contributions of S. A. Gostimsky (M. V. Lomonosov Moscow State University), and M. Sugimoto (Okayama University, Institute of Bioresources, Okayama, Japan) should be especially noted.

Plant Growth on the International Space Station has Global Impacts on Earth

Understanding the effects of gravity on plant life is essential in preparing for human exploration beyond low-Earth orbit. The ability to produce high-energy, low-mass food sources during spaceflight will enable the maintenance of crew health during long-duration missions while having a reduced impact on resources necessary for long-distance travel.

The Advanced Astroculture™ (ADVASC) investigation, led by Weijia Zhou, Ph.D., formerly of the Wisconsin Center for Space Automation and Robotics, University of Wisconsin-Madison, explored the benefits of using microgravity to create custom crops that can withstand the inhospitable climates of space, can resist pestilence, and will need less volume in which to grow. ADVASC was performed over several ISS expeditions where it grew two generations of Arabidopsis thaliana (i.e., a rapidly growing, flowering plant in the mustard family that has been grown on many space missions), and soybean plants from seed to seed in space using the ADVASC payload—an autonomously operated plant growth unit. The ability to grow plants from seeds through several generations has proven to be challenging in space and is critical in developing hardware and operational concepts to take human explorers farther beyond low-Earth orbit.

While serving as a unique plant-growth chamber, the ADVASC hardware design has also contributed to national security, cancer-fighting pharmaceuticals and educational tools for students. ADVASC's novel air scrubber was designed to remove ethylene from the chamber atmosphere to increase longevity of the produce. Ethylene—a naturally occurring, odorless, colorless gas given off by plants—hastens the ripening of fruits and the aging of flowers, thus encouraging decay. In closed growing environments such as a spacecraft or terrestrial greenhouse, ethylene builds up quickly. As a result, plants mature too fast. Removing ethylene, therefore, is important to preserving crops not just in space, but also on Earth, where grocers and florists have an interest in longer product shelf life.

The ethylene-reduction device, also called the ethylene "scrubber," draws air through tubes that are coated in thin layers of titanium dioxide. The insides of the tubes are exposed to ultraviolet light, which creates a simple chemical reaction that converts the ethylene into trace amounts of water and carbon dioxide, both of which are actually good for plants.

KES Science & Technology Inc., a Georgia-based company specializing in sustaining perishable foods, licensed the ethylene-scrubbing technology from the University of Wisconsin. KES partnered with Akida Holdings, of Jacksonville, Florida, which now markets the NASA-developed technology as Airocide. According to the company, Airocide is the only air purifier that completely destroys airborne bacteria, mold, fungi, mycotoxins, viruses, volatile organic compounds such as ethylene, and odors. The device has no filters that need changing and produces no harmful by-products, such as the ozone created by some filtration systems.

Food preservation customers include supermarkets, produce distribution facilities, food processing plants, wineries, distilleries, restaurants and large floral shops. Reeves Floral, an Airocide user, reported 92% reduction in airborne mold and a 58% drop in airborne bacteria levels after only 24 hours of operation in its floral storage warehouse. These units in walk-in coolers can preserve freshness of produce during storage and transport, increase safety in food preparation areas, kill bacterial contaminants in flowers, and protect against spoilage and contaminants.

Units also have been deployed to India and the Gulf Cooperation Council, which includes the countries of Bahrain, Kuwait, Qatar, Oman, Saudi Arabia, and the United Arab Emirates. In these areas, where refrigerated trucks carry groceries from rural farmland to towns miles away, the unit preserves freshness and prevents food spoilage.

In addition to eliminating virtually all known airborne germs and diseases, the technology reduces the burden on high-efficiency particulate air filters and laminar flow environments.

The units also operate in doctors' clinics, operating rooms, neonatal wards, and waiting areas, an often-overlooked location rife with germs and bacteria such as respiratory influenza or mycobacterium tuberculosis, and which are frequented by people with compromised immune systems. Units made operating rooms safer for all inhabitants by removing harmful bacteria such as methicillin-resistant Staphylococcus aureus and vancomycin-resistant Enterococcus, and the fungi Penicillium and Aspergillus. In addition to eliminating virtually all known airborne germs and diseases, the technology reduces the burden on high-efficiency particulate air filters and laminar flow environments.

Adaptions for use in everyday living environments include eliminating mold, mildew, germs and unwanted odors in hotel rooms and offices, where illnesses caused by airborne organisms can lower productivity. Airocide even offers a consumer line that makes the same technology used on the space station available in homes to help eliminate bacteria, mold and fungi as well as allergens such as dust and dander, and potentially harmful particulate matter.

Astronaut Peggy Whitson with the ADVASC soybean plant growth experiment during Expedition 5.
Image credit: NASA

Air Purifier Technology Helps Prevent Global Food Waste

To conduct the Advanced Astroculture (ADVASC) investigations aboard the International Space Station, engineers needed to solve the challenge of removing ethelyne from the air. Airocide, an air purifier derived from ADVASC ethylene scrubbing technology, led to the direct investment of $25 million toward the development of production capacity of 60,000 to 100,000 residential units in the United States per year (est. retail value $36 - $90 million per yr). Airocide technology is used across a spectrum of commercial applications, including more than 100 Napa Valley vineyards, hospitals, commercial markets such as Whole Foods, and food manufacturers such as Kraft Foods and the Coca-Cola Company. With more than 320 million tons of fruits and vegetables wasted each year, technologies such as Airocide aim to reduce global food waste and provide a new avenue for global consumers to safely preserve their foods for longer.

Heart Health and Biorhythms

Studying spaceflight effects on the cardiovascular system has led to the creation of unique instruments that can be used on Earth for the detection of the earliest deviations in health status. These technologies are now used to examine motor vehicle drivers and civil aviation pilots to evaluate risks and prevent accidents. Twenty-four-hour electrocardiograms of astronauts were also analyzed to understand the space environment's effect on biological rhythm and cardiac autonomic nervous activity, which led to recommendations for maintaining a well-balanced biological rhythm on Earth. One of these recommendations is maintenance of a regular sleep schedule. To study the sleep patterns of cosmonauts, information is recorded via a miniature device that fits in their pocket, and the data are sent to Earth for analysis of sleep quality. An Earth model of this device is placed under the pillow or mattress to record movements related to heart and breathing.

Space Cardiology for the Benefit of Health Care

The cardiovascular system plays an exceptionally important role in cosmonauts' physical adaptation to long-term weightlessness. The scientific experiment Puls (2002 to the present) and the experiment Pneumocard (2007 through 2012) were performed regularly on the International Space Station (ISS) to study spaceflight effects on the cardiovascular system. Experiment Cardiovector is a logical continuation of the experiments Puls and Pneumocard, which gives the opportunity to assess cardiac function and autonomic cardiovascular and respiratory control using easy, cheap, reliable and non-invasive techniques for cardiovascular monitoring. This scientific experiment involved the whole Russian space station crew on the ISS and was performed regularly since 2014. These studies have provided a tremendous amount of information about space cardiology that has resulted in new technologies being successfully used to evaluate the body's functional reserves, to determine the degree of stress on regulatory systems, and to assess the risk of development of disease. These new technologies served as the basis both for further development of cardiological systems on the ISS and for the creation of unique sets of instruments that can be used in health care practice. On Earth, the hardware-software complex Ecosan-2007 is a multipurpose instrument for early detection of the earliest deviations in health status. Ecosan-2007 is based on the principle of prenosological diagnosis,

Research using the Ecosan-2007 complex in isolation experiment Mars-500.

Image credit: Institute of Biomedical Problems of the Russian Academy of Sciences

These studies have provided a tremendous amount of information about space cardiology that has resulted in new technologies being successfully used to evaluate the body's functional reserves, to determine the degree of stress on regulatory systems, and to assess the risk of development of disease.

Experiment Cardiovector aboard the ISS.
Image credit: ROSCOSMOS

which arose in space medicine. Prenosological refers to the study of changes in the body that precede their development. This device is now used to examine motor vehicle drivers, civil aviation pilots, and test subjects in experiments on Earth involving various stress factors.

A study that used the Ecosan-2007 to detect early health issues among 105 bus drivers showed that more than 30% of the drivers were in prenosological and premorbid states, which sharply increases the risk of motor vehicle accidents. During examinations of civil aviation pilots, the use of Ecosan-2007 showed that long-term, work-related chronic stress increases the risk development of pathologies, which should be considered during the expert evaluation of fitness for flight, especially for people over the age of 50.

The Ecosan-2007 complex was also used in a 520-day experiment on Earth that simulated a flight to Mars. Monthly examinations of the "Martian" crew located in a pressurized mock-up of an interplanetary spacecraft and, at the same time, of volunteer test subjects in control groups in 12 different regions of the world were performed. Long-term telemedicine of medical-environmental research using the Ecosan-2007 complex will be the prototype of a future system of individual prenosological monitoring, which will be based on space cardiology methods.

The results of the studies performed on Earth using the Ecosan-2007 complex served as a tool for Earth-based clinical use and as the basis for the further development of space cardiology technologies. The space device Cosmocard is developing the methodology that was used in the Ecosan-2007 for electrocardiogram dispersion mapping and can be used for the non-invasive study of the energy-metabolic characteristics of the cardiac muscle. This method is actively used in clinic for the diagnosis of cardiovascular diseases. We hope that two new experiments—Cardiovector and Cosmocard—that have been developed for the ISS will allow us to answer questions about spatial distribution of cardiac contraction energy in microgravity, ratio of the right and left part of the heart, and relationship between the hemodynamic and energy features of the heart in different periods of a long-term space mission.

Vascular Studies in Space: Good for Everyone's Heart

Perhaps the human heart does not really yearn to be free—at least not from gravity. Microgravity affects the heart's ability to pump blood and provide oxygen to cells throughout the body, which can have serious health consequences, especially upon landing on a planet. The heart adapts to changes in blood distribution and pressure in weightlessness, which can cause dizziness or fainting upon return to the ground. Four Canadian experiments, funded by CSA and led by Dr. Richard Hughson of the University of Waterloo, have looked into why this happens in order to develop effective countermeasures, help maintain the health of space travelers and reduce the detrimental effect of aging on Earth.

The first experiment, Cardiovascular and Cerebro-vascular Control on Return from the International Space Station (CCISS), found that important differences exist among individuals. The cardiovascular system ensures continuous supply of oxygenated blood to the brain

These spaceflight studies provide a platform to explore potential mechanisms and help develop interventions to slow vascular aging and improve health and quality of life for everyone—regardless of whether their hearts are free of gravity.

and the body. Heart rate response to changes in blood pressure varied between astronauts. These results could point to a need for some crew members to do more exercise or use other measures to help protect their blood pressure response on return to Earth. CCISS suggested that constant elevation in blood pressure in the brain while in space, reduced daily physical activity, and constant exposure to slightly higher levels of carbon dioxide in cabin air may impair how blood vessels of the brain respond to changes in blood pressure and carbon dioxide levels.

Results from the second experiment, Cardiovascular Health Consequences of Long-Duration Space Flight (Vascular), highlighted individual variability in the control of arterial blood pressure by the hormones in the blood, with some differences in male and female astronauts. Interestingly, some crew members return from the ISS with much stiffer arteries than when they went into space. The Vascular study confirmed an increase in carotid artery stiffness indicators, in both male and female astronauts, of the magnitude expected from 10 to 20 years of normal aging. Arterial stiffening in space and on Earth is often linked to an increased blood pressure and elevated risk for cardiovascular disease. Some results from the study revealed that insulin resistance occurs during spaceflight, possibly due to reduced physical activity. Insulin resistance on Earth leads to increased blood sugar and increased risk of developing type 2 diabetes. All these results suggested that the astronauts' exercise routine was not sufficient to counteract the lifestyle of weightlessness and pointed to the need for further work on appropriate countermeasures to help maintain astronaut health.

The follow-on study, Cardiac and Vessel Structure and Function with Long-Duration Space Flight and Recovery (Vascular Echo), is examining changes in blood vessels and the heart while in space and following return to Earth. More specifically, this study will determine how arteries and the heart react to changes in blood pressure, whether blood flow after exercise is changed by spaceflight, and identify warning signs of arterial stiffening in the blood. This study uses ultrasound and blood samples to provide immediate feedback on the development of arterial stiffness and cardiac changes during spaceflight. It explores a potential measure to reduce the excess amount of blood in the upper body by using a leg cuff, and less-complicated ways than ultrasound to measure changes in arterial stiffness.

Finally, a fourth study—The space environment causes acceleration of vascular aging: roles of hypogravity, nutrition and radiation (Vascular Aging)—will try to confirm if and when insulin resistance, a precursor of type 2 diabetes, develops during a space mission, clarify the effect of radiation exposure and track the recovery process after return on cardiovascular health.

Cardiovascular disease is the number one cause of death on Earth, where research has associated physical inactivity with the development of risk factors, including arterial stiffness and insulin resistance. These spaceflight studies provide a platform to explore potential mechanisms and help develop interventions to slow vascular aging and improve health and quality of life for everyone—regardless of whether their hearts are free of gravity.

Dressing Astronauts for Return to Earth

Astronauts on the ISS perform research with mice and spiders, and not a single crew member ever faints. When those same astronauts come back to Earth, though, it can be a different story.

Postflight orthostatic intolerance, or the inability to maintain blood pressure while in an upright position, can cause astronauts to faint upon return from space. Between 60% and 80% of astronauts experience orthostatic intolerance after long-duration missions. This represents a potential hazard for crew members during re-entry and after landing, especially should there be a need for an emergency exit from the spacecraft.

Countermeasures such as fluid loading and compression garments have demonstrated some effectiveness in preventing this phenomenon. However, neither is completely effective at all phases of landing and egress. Therefore, research continues.

NASA and ROSCOSMOS have used garments that provide lower-body compression as a countermeasure to protect astronauts and cosmonauts during and after return from spaceflight.

A next-generation compression garment design resulted from a series of studies conducted by NASA's

NASA continues to improve compression garments that allow astronauts to dress for a more successful return to Earth.

Cardiovascular and Vision Laboratory to evaluate these garments, including Evaluation of Compression Garments as Countermeasures to Orthostatic Intolerance and Evaluation of Commercial Compression Garments as a Countermeasure to Post-Spaceflight Orthostatic Intolerance. Following that initial work, additional studies evaluated different amounts of lower-body coverage and compression using test subjects in the laboratory, after bed rest (i.e., a way to simulate spaceflight effects), and in astronauts after Space Shuttle missions.

NASA then partnered with a commercial manufacturer to produce a custom-fitted garment that is able to provide continuous coverage across the lower body, with highest compression applied at the feet and decreasing up to just above the waist. Designers modified a commercially available garment with a similar compression profile that worked well in the laboratory, thus creating garments that are relatively easy to put on in weightlessness and comfortable to wear during re-entry and after landing. The symptoms of orthostatic intolerance are expected to be most prevalent immediately after landing.

Although these garments are designed specifically for use by astronauts, the Cardiovascular and Vision Laboratory currently works with university-based cardiologists on tests of a similar garment for clinical patients prone to fainting on Earth. Orthostatic intolerance affects approximately 500,000 Americans and can result in significant symptoms. It can also hamper a person's ability to participate in normal activities of daily life.

The next step is validating the performance of these garments during recovery from long-duration spaceflight in an ongoing study, Recovery of Functional Performance Following Long Duration Space Flight. Preliminary evidence suggests that these custom-made, gradient compression garments that include abdominal compression offer relief from orthostatic intolerance and its symptoms.

NASA continues to improve compression garments that allow astronauts to dress for a more successful return to Earth.

Innovative Space-based Device Promotes Restful Sleep on Earth

Interest in the study of nighttime sleep in weightlessness has grown since the first steps of space exploration. Despite many years of investigations, researchers still lack experimental data to judge sleep quality and details of changes in sleep caused by peculiar factors of spaceflight. Indeed, normal, good-quality sleep is the basis for maintaining the necessary, high psychological functioning and good physical condition of cosmonauts. However, the clinical method used to study sleep (polysomnography) requires the use of a large number of sensors, which disturbs normal sleep, requires time and is too complex for spaceflight.

Thus, data on the sleep quality of cosmonauts in long-term weightlessness have been extremely limited.

In 2007, a new device, Sonocard, arrived on the Russian Segment of the ISS, making it possible to study sleep with a miniature device the size of a deck of cards. The device is placed on the left in the top pocket of the cosmonaut's T-shirt before sleep, and its sensor elicits micro-fluctuations of the chest wall that are related to heart function. Upon wake-up, the information recorded during the night is sent to Earth for retrospective detail analysis in laboratory.

Sonocard provides a contactless recording of physiological signals, and its use does not require attaching electrodes or special sensors to the body. Instead, it acquires its data by recording all the vibrations that are elicited by the sensor-accelerometer. Pulse rate, breathing rate, movement activity and heart rhythm variability are obtained. This method is successfully used in various fields of medicine and physiology to assess the state of the basic body functions. Space medicine was one of its first fields of application. To date, a large amount of experience has been accumulated on its use to assess the functional condition of cosmonauts during spaceflight. Changes in the activity of the sympathetic and parasympathetic regulation chains in first hours after falling asleep and last hours before waking up are determined when analyzing the data obtained during sleep. This makes it possible to assess to what extent the body was able to rest during sleep, and how much the body replenished the functional reserves that were spent the day before.

Sonocard provides a contactless recording of physiological signals, and its use does not require attaching electrodes or special sensors to the body.

Scientific experiments using the Sonocard device were conducted on the ISS on all Russian cosmonauts from 2007 to 2012. A large amount of information on sleep in weightlessness has been gathered over the course of 5 years. For the first time, it is possible to discuss results that are not impacted by factors of workload and psycho-emotional stress, which are always present during the day while carrying out science experiments under the normal flight program. A flight index sleep quality showed that the quality of sleep on average for the entire flight for all 22 participants in the experiment was 77.4%.

The Sonocard contactless method of sleep study that was created for use on the space station has been successfully used on Earth. The Earth model used a sensor that was designed in the form of a plate to be placed under the pillow or mattress to record a person's body movements related to heart and breathing rate. The signals recorded during the night are downloaded to a computer and analyzed according to the methods already proven in space research.

The new software system called Cardioson was tested in a series of experiments on Earth, including a long-term, 520-day experiment simulating a flight to Mars and isolation, and the "Sirius-17" mission. The unique research experience of the cosmonauts' functional state during sleep can be further developed in two directions: creation of new, more-effective systems of evaluating sleep in space for the simultaneous medical control of all crew members; and development of similar devices for controlling the quality of sleep in the interests of public health care practice.

Crew member sets up the Sonocard device before sleep in spaceflight.

Image credit: ROSCOSMOS

Cardioson system—Earth analog of the Sonocard space device.

Image credit: Institute of Biomedical Problems of the Russian Academy of Sciences

Improving Balance and Movement

A new technology developed to correct motor disturbances in weightlessness has been used to treat patients with cerebral palsy, stroke, spinal cord injuries, balance problems and motor decline due to aging. Assessment of eye movement reactions of cosmonauts, preflight and postflight, has led to faster and less-expensive diagnoses and treatment of patients suffering from vertigo, dizziness and equilibrium disturbances. A patented computerized, non-pharmacological method of preventing and correcting unfavorable perception and sensorimotor reactions is used to train patients and astronauts to acquire the ability to suppress vertigo, dizziness and equilibrium disturbances.

A system of hardware and software that collects information on body movements of astronauts on the International Space Station (ISS) has led to motor imagery protocols used in the research environment of a hospital in Rome in treatment of adult stroke patients and children with cerebral palsy. Other body movement research on the ISS led to the development of a suit for astronauts to compensate for the lack of daily loading from gravity. The clinical version of this suit is used for the comprehensive and drug-free treatment of cerebral palsy in children in Russia. Another clinical variation of this suit is used on patients who have suffered from stroke or brain trauma.

New Technology Simulates Microgravity and Improves Balance on Earth

Spaceflight opportunities, such as that of the ISS, facilitated the development of Earth-based models of weightlessness and opened the door to studying the effects of the elimination of gravity. Over the 20 years since the ISS came into existence, the Russian Institute of Biomedical Problems (IBMP) has compiled a large amount of data—information and facts that have made it possible to switch from describing occurrences and phenomena to developing theories about the role and place of gravitational mechanisms in various bodily systems.

One example of an evolution in the development of new knowledge is the discovery of the leading triggering role in maintaining vertical posture of sensory organs called Vater-Paccini corpuscles, which are located in the soles of the feet. These receptors were discovered back in the 19th century; however, their role in gravireception was established recently, thanks to ground-based simulation studies designed to keep cosmonauts' balance healthy in long-duration spaceflights. As a result of these studies, a unique piece of technology was developed to help to correct the motor disturbances in individuals with central nervous system dysfunction, injuries, balance problems and motor decline due to aging.

Ground-based studies at IBMP identified a particular pattern of stabilization between body loading on the soles of the feet and subsequent motor stabilization processes associated with brain and spinal cord activities. The knowledge obtained revealed that the development of sensory-motor disturbances may be prevented by means of "artificial" support stimuli applied to the bottoms of the feet. The research results led to the development of new technology, the "support unloading compensator," which is a device that stimulates the support zones of the foot in natural human gait.

The uniqueness of this device lies in its ability to simulate the physical parameters that the support receptor or the foot receives during walking: the magnitude of pressure, temporal characteristics, duration of impact, intervals between stimulation

Today, this technology is being used in the most acute phase of stroke and facilitates more significant regression of motor disturbances and earlier recovery of locomotion than traditional treatment methods.

The support unloading compensator.

Image credit: Aerospace Medical Center and Technology

of the heel and metatarsal support zones, and intervals between stimulation of the right and left foot.

However, the disturbances of muscle tone and coordination of movement are not inherent exclusively to weightlessness. Diseases of the central nervous system, brain injuries of various types, long-term motor unloading in aging, as well as some specific occupational conditions are also accompanied by the development of the aforementioned changes. Based on these data, IBMP scientists are working jointly with commercial companies to introduce motor disturbances corrective measures that were developed for weightlessness into the practice of treating and rehabilitating patients with profound motor lesions that are due to cerebral palsy, stroke, and brain and spinal cord injuries.

Between 2005 and 2011, the Center for Aerospace Medicine developed a clinical version of the support unloading compensator—the Korvit—and obtained all approval documents and licenses.

Today, this technology is being used in the most acute phase of stroke and facilitates more significant regression of motor disturbances and earlier recovery of locomotion than traditional treatment methods. Of particular interest are the data on prevention of muscle spasticity development of limbs affected by paresis in cases when the Korvit device is used in the first hours after the onset of a stroke.

The support unloading compensator used on children.

Image credit: Aerospace Medical Center and Technology

The use of the support stimulation method in children during the early recovery phase after surgical treatment for fractures of the calf bones has facilitated the reduction of edema by 17% to 20%, and an increase in the range of motion in the ankle joint by 45% as early as the first 72 hours after surgery. Children who do not receive such treatment experience edema lasting 6 to 8 days, which hinders motion in the injured limb and retards regenerative processes.

The use of the Korvit apparatus in the integrated rehabilitation of cerebral palsy patients has made it possible to maximize restoration of the balance of strength between extensor and flexor muscles, particularly in an upright position, and to normalize the functions of standing and walking, as well as coordination control of various classes of movements.

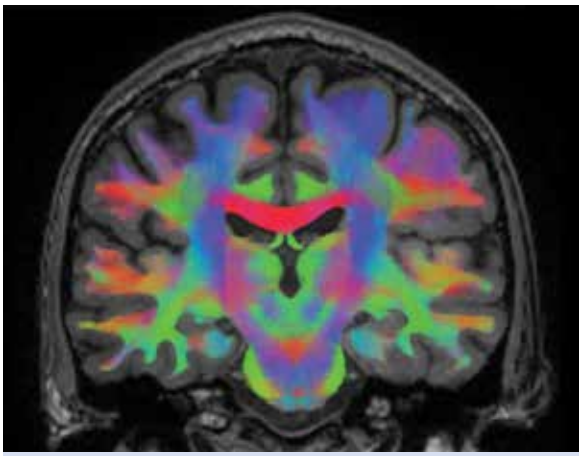
Countering Neurological Maladaptation

European Space Agency (ESA) research has been uncovering important aspects of how the structure and function of the brain adapt due to exposure to spaceflight conditions; e.g., how central processing of information is altered under spaceflight conditions and on return to Earth. The findings of this research are crucial for enabling the safe planning of future human exploration missions beyond low-Earth orbit, and also have clinical implications on Earth within a wide range of neurological disorders.

The brain functions through electrical signals to perform every voluntary and involuntary activity in our body. This electrical activity is important for complex brain function and helps us to characterize brain dynamics and brain states made visually accessible through techniques such as EEG and MRI. Changes in electrical activity are a normal part of human daily life—e.g., brain wave changes associated with waking up and falling asleep. However, changes in electrical activity can also be a sign of some maladaptation, which could result in, or be a sign of, cognitive dysfunction.

Two ESA ISS experiments—Neurospat and Brain-DTI—have already produced positive results published in several renowned peer-reviewed journals in 2016 and 2017. Neurospat compared inflight to ground EEG measurements and discovered a greater contribution from the motor cortex (involved in control of voluntary movements) when performing tasks in a visually attentive state in orbit. The Brain-DTI (preflight/postflight) experiment uses advanced MRI methods to help accurately determine and map the effect of spaceflight-induced changes in brain structure and function on the motor, vestibular and cognitive systems. Brain-DTI has already discovered alterations in vestibular and motor-related regions of the brain, which could account for space motion sickness as well as reduced vestibular function and motor control abilities in space and at re-entry. This research has also been backed up by similar results from parabolic flight campaigns. Vestibular and motor-related regions of the brain seem to be critically involved. Hampered sensory inputs from the inner ear could have an effect on brain areas where integration of the different sensory inputs takes place. Observations of problems with motor abilities in returning space crew suggest plausible alterations of structure and function of the cerebellum (responsible for coordination and fine motor control).

The findings of this research are crucial for enabling the safe planning of future human exploration missions beyond low-Earth orbit, and also have clinical implications on Earth within a wide range of neurological disorders.



An MRI scan using of a volunteer's brain for the BRAIN-DTI experiment using tractography to show neural networks.

Image credit: University of Antwerp

Motor imagery, widely used in sports, could prove to be a useful countermeasure in this neurological adaptation. This technique involves mentally visualizing a specific motor task, and mentally feeling muscle contractions in advance of performing that task. It has been proven that motor imagery activates similar brain regions, as is the case with executed movements. This technique is finding its way into different rehabilitation and pain management scenarios such as post-stroke motor rehabilitation. The technique offers an inexpensive and rather simple approach to prepare space travelers for the absence of gravity and re-adaptation phase when coming back to Earth. Transcranial magnetic stimulation also offers a possible countermeasure by allowing non-invasive stimulation of an area of the cortex through the scalp by means

of brief electrical pulses. This portable method could be easily implemented in space and potentially used to stimulate muscle contractions to counteract lower extremity dysfunction on long-duration space missions.

This research is improving our understanding of how the brain reacts to and behaves during spaceflight. This is a crucial step in the development of appropriate countermeasures to enable safe and successful exploration missions in the future, especially when considering critical crew tasks such as spacewalks or surface-based extravehicular activity, which could be hampered by impaired motor control, movement and coordination. Higher cognitive tasks (e.g., working memory, risk-taking and dual-tasking) might also be influenced, possibly leading to unacceptable risks and hazards. Research in this area will also help to determine any potential long-term effects of such adaptation in space and on return to Earth, and to feed into associated recovery and rehabilitation planning. Additionally, research findings may have direct and indirect clinical impacts and could be transferred to multiple neurological and psychiatric diseases and pathologies on Earth, such as patients suffering from neurodegenerative disorders or vestibular problems, as well as members of the elderly population who may be coping with multisensory deficit syndromes, immobilization and inactivity.

New Way to Assess Neurovestibular System Health in Space Also Benefits Those on Earth

Among the many problems that have confronted the medical sciences since humans first began exploring space, a main one is adaptation to the conditions of changed gravitational force. Upon arrival in weightlessness (the first 3 to 7 days) and upon the return to Earth (from landing to 3 to 5 days later), virtually all crew members experience a number of negative reactions and sensory disorders (e.g., orientation illusions, vertigo, dizziness, problems focusing on and tracking visual objects), which are perceived as uncomfortable and can be accompanied by space motion sickness.

In weightlessness, information received from the vestibular apparatus within the inner ear does not align with information received from other sensory systems; therefore, the typical sensory links are broken and the brain cannot correctly interpret the incoming signals at the beginning of flight, thereby leading to the development of space motion sickness. As a result, this situation causes a decrease in the quality

Space experiment Virtual aboard the ISS (2013). Image credit: ROSCOSMOS

of performance of work tasks, particularly those relating to visual tracking accuracy. It is likely that the unsuccessful docking of spacecraft, errors in structural assembly, and other instances of errors in manual control that have occurred in orbit were often caused by disturbances in the function of tracking moving space objects because of changes in sensory functions.

Analysis of data that was accumulated in a series of scientific experiments before, during and after spaceflights on the Salyut-6, Salyut-7, MIR and ISS has led the Institute of Biomedical Problems in Russia to develop a method that uses computerized systems—named OculoStim-CM, Virtual and Sensomotor—that can accurately assess the state of vestibular function, intersensory interactions, spatial orientation, and visual tracking (Russian Federation patent #2307575 dated 10/10/2007, Kornilova L. N. et al.).

The use of a special test battery makes it possible to evaluate the disruptions that are occurring in various forms of eye movements and, given the known mechanisms of how these movements are performed, to find the causes of these disturbances.

Application of the OculoStim-CM hardware and virtual reality glasses in a joint 60-day bedrest experiment in Cologne, Germany (2016).

Image credit: Institute of Biomedical Problems

At the basis of the method lies the assessment of eye movement reactions—visual tracking tests that are conducted both with visual targets (stimuli) on a clean (black) field on the screen and against a backdrop of additional visual interferences (diffuse spots/ellipses moving horizontally or vertically) to "irritate" the peripheral vision. During the testing under differing conditions, movements of the eyes (by electro- and video- oculography) and the head (using angular rate sensors and accelerometers) are recorded.

The eye-movement system is controlled by a complex hierarchy of innervation mechanisms located at different levels of the nervous system. The use of a special test battery makes it possible to evaluate the disruptions that are occurring in various forms of eye movements and, given the known mechanisms of how these movements are performed, to find the causes of these disturbances.

This method has been actively used during prolonged spaceflight aboard the ISS in a space experiment called Virtual since 2013, and after crew members return to Earth during Sensory Adaptation study since 2001.

Recent studies have shown that repeated spaceflight leads to a dramatic, statistically significant reduction in the duration of postflight re-adaptation with significantly less severe vestibular disorders. Cosmonauts with a prior experience of being in microgravity had significantly changed vestibular reactions only on return plus 1 to 2 days postflight whereas cosmonauts who were in long-term spaceflight for the first time had symptoms of space motion sickness and vestibular disorders up to return plus 8 to 9 days postflight.

The procedure and hardware/software systems developed for spaceflight have also demonstrated effectiveness of the computerized method and hardware/software systems for use in diagnosing conditions of the vestibular and its related sensory systems (primarily visual), as well as in assessing the stability of static and dynamic spatial orientation on Earth. The systems have particularly been useful in experiments simulating weightlessness (i.e., immersion and bed rest), in examining highly qualified athletes (e.g., high-performance sports: gymnastics, figure and speed skating, target shooting, etc.), in diagnosing and treating patients who are suffering from dizziness and equilibrium disturbances, and in evaluating the effectiveness of medications (i.e., betahistine drugs Betaver and Betaserc). The OculoStim-CM complex is successfully certified for use in clinical studies and has been used in diagnostics of more than 200 patients with vertigo, dizziness and equilibrium disturbances, together with specialists from the nervous disease department of the I. M. Sechenov First Moscow State Medical University, the Academician Alexander Vein Clinic for the Treatment of Headaches and Vegetative Disorders, the Federal Scientific Clinical Center of Otorhinolaryngology, and the Research Center of Neurology. Such application in clinical practice has made it possible to develop diagnostic criteria to determine the type of vestibular disturbance, while offering a rapid, less-expensive initial differential diagnosis of dizziness and balance disturbances compared to traditional clinical testing.

Space Research Leads to Non-pharmacological Treatment and Prevention of Vertigo, Dizziness and Equilibrium disturbances

The history of spaceflight has shown that initial introduction to the weightlessness environment, such as that of the ISS, can lead to space motion sickness, which makes crew members feel dizzy and uncoordinated, and even impacting their ability to track objects with their eyes. The result can be a negative effect both on the health of crew members and on the quality of their work performance during flight.

At present, medications are typically used to eliminate the symptoms of space motion sickness; however, these medications come with contraindications and side effects that can have a negative effect on various types of professional activity. Therefore, there is an

The suppression of negative reactions during flight using the fixation reflex has been successfully applied by crew members aboard the ISS since 2013.

obvious need to develop non-pharmacological methods of preventing and treating space motion sickness.

It is well known that people in extreme professions such as mountain climbers, athletes, acrobats and ballet dancers develop the capability to suppress unfavorable vestibular reactions at the moment high accelerations act on them by developing a "fixation reflex." However, attempts by many clinicians to treat patients with vestibular problems using the same methods have been unsuccessful because of the vestibular challenges that are unique to this population. Therefore, experts at the vestibular physiology laboratory at the Institute of Biomedical Problems developed and patented a "Computerized method of preventing and correcting unfavorable perception and sensorimotor reactions" (Russian Federation patent #2301622 dated 06/27/2007, Kornilova L. N. et al.). The innovation of this method is in creating a unique approach to the training of patients depending on their disease (i.e., type of vestibulopathy) and in selecting the most effective means of training (e.g., visual, vestibular, or combined) by using biofeedback.

Depending on the nature of the vertigo, dizziness or equilibrium disorder and of his/her disease (type of vestibulopathy), a series of patient training sessions is conducted to develop a unique fixation reflex using biofeedback that is provided by the computer using this method to record eye and head movements.

Training is conducted until the negative reactions (i.e., vertgo, dizziness and equilibrium disturbances) disappear or are significantly reduced. The therapeutic effect of the training is assessed through a follow-up clinical/neurological examination, which includes using the computerized method of comprehensively assessing the condition of vestibular function and visual tracking function (Russian Federation patent #2307575 dated 10/10/07, Kornilova L. N. et al.) and the specially developed OculoStim-CM hardware complex. The indicator of training success is the suppression of experimentally induced negative reactions (full or partial) during the action of visual and vestibular stimuli while fixing the gaze on an imagined target.

The non-pharmacological computerized method for treating and preventing vertigo, dizziness and equilibrium disturbances was tested in clinical conditions jointly with specialists from the nervous disease department of the I. M. Sechenov First Moscow State Medical University, the Academician Alexander Vein Clinic for the Treatment of Headaches and Vegetative Disorders, the Federal Scientific Clinical Center of Otorhinolaryngology, and the Research Center of Neurology.

Results of the clinical work demonstrated that patients acquired the capacity to fixate on and hold their gaze on both real and imagined targets, thus suppressing (fully or partially) vertigo, dizziness, nystagmus, and equilibrium disturbances. It was shown that training effectiveness depended not only on the disorder (i.e., type of vestibulopathy), but also on the type of training selected. For patients with peripheral vestibulopathies, the most effective was visual training; for patients with central vestibulopathies, the vestibular method was the best option; and for patients with psychogenic vestibulopathies, the combined method was preferred.

Analysis of special questionnaires demonstrated that all patients with psychogenic, 91% of patients with peripheral, and 80% of patients with central vestibulopathies subjectively noted "good suppression of vertigo in everyday conditions" and "improvement in general adaptation to real life conditions."

Visual method of training (Laboratory of Vestibular Physiology, 2013).

Image credit: Institute of Biomedical Problems

The effectiveness of the non-pharmacological computerized method has made it a good candidate for use both during the preflight training of ISS crew members, and during spaceflight, to suppress the symptoms of space motion sickness. The suppression of negative reactions during flight using the fixation reflex has been successfully applied by crew members aboard the ISS since 2013.

Moreover, recent studies (2017-2018) in patients with Parkinson's disease, and carried out in the Research Center of Neurology, Moscow, have shown that such an approach using of the OculoStim-CM hardware and a special battery of computerized tests allow us to solve the problem of objectifying the neurological deficit and assess the disorders in trajectories of head and eyes movements. Early diagnosis and properly initiated treatment play an important role in stabilizing the progression of Parkinson's disease. Computerized methods and OculoStim-CM hardware were originally developed for space research. However, their clinical application now opens the possibility of early diagnosis of disorders in Parkinson's disease, assessing the dynamics of these disorders and, in the future, proceeding to the screening assessment of these disorders in patients at risk when conventional diagnostic methods are ineffective.

Space Technologies in Rehabilitation Practice

The increase in the duration of a crewed spaceflight has resulted in the need to improve the system of medical support and monitor the health status of cosmonauts. Traditional means and methods such as physical exercise are impossible to perform, in some cases, due to a time deficit limited vehicle space, etc.

In preparation for longer spaceflights, specialists from IBMP and the company Zvezda developed the axial loading suit, Penguin, as the space device that could compensate for the deficit of axial loading of the body onboard the spacecraft.

The idea to load the musculoskeletal system of the cosmonaut by using a preventive load suit, which creates a constant load on the skeleton, leg muscles and torso, resulted in a dynamic proprioceptive correction method. This suit was applied in health care for the treatment of children with cerebral palsy, thereby shortening the time needed to develop walking skills.

Today, a wide range of experience has been accumulated in the application of Regent in patients with focal defeats of the central nervous system.

The search for methods of restorative treatment for patients with ischemic stroke and traumatic brain injury ended with the development of a modified version of Penguin. This therapeutic suit is called Regent.

Today, a wide range of experience has been accumulated in the application of Regent in patients with focal defects of the central nervous system. A total of 112 clinics, which provide specialized preventive, curative and rehabilitation assistance in the Russian Federation, use this technology in rehabilitation practice.

Left: The Adeli treatment suit in use for pediatric rehabilitation. Right: The Regent suit in use for patient rehabilitation.

Images credit: Aerospace Medical Center and Technology, Russia

View of Red-Green Southern Aurora taken during a night pass by the Expedition 52 crew aboard the International Space Station.

Image credit: NASA

Earth Observation and Disaster Response

Earth Observation

The International Space Station (ISS) is a “global observation and diagnosis station.” It promotes international Earth observations aimed at understanding and resolving the environmental issues of our home planet. A wide variety of Earth observation payloads can be attached to the exposed facilities on the space station’s exterior as well as in the Window Observational Research Facility located within the Destiny module. The presence of a human crew also provides a unique capability for real-time observation of the Earth, and “on the fly” data collection using hand-held digital cameras, and the astronauts may also provide input to ground personnel programming the space station’s automated Earth observation systems. Several instruments are currently collecting data from the space station; in addition, some instruments have completed their data collection missions, with other remote sensing systems in development or proposed by researchers from the partner countries, NASA, academic institutions and corporations. The existing international partnerships, fundamental to the space station, facilitate data sharing that can benefit people around the world and promote international collaboration on other Earth observation activities. The space station contributes to humanity by collecting data on the global climate, environmental change and natural hazards using its unique complement of crew-operated and automated Earth observation payloads.

Environmental Earth Observations

The International Space Station (ISS) offers a unique vantage for observing the Earth's ecosystems and atmosphere with hands-on and automated equipment. The size, power, and data transfer capabilities of the space station enable a wide range of sophisticated sensor systems including optical multispectral and hyperspectral imaging systems for examining the Earth's land surface and coastal oceans, as well as active radar and Light Detection and Ranging (LiDAR) systems useful for investigating sea surface winds and atmospheric aerosol transportation patterns. Astronauts using hand-held digital cameras provide an additional imaging capability for obtaining both detailed images of the Earth surface as well as sweeping panoramic views of its atmosphere. This flexibility is an advantage over sensors on unmanned spacecraft, especially when unexpected natural events such as volcanic eruptions and earthquakes occur.

Earth Remote Sensing from the International Space Station

The space station is a capable platform for Earth remote sensing with sufficient power and data infrastructure to support a variety of internal and external sensors. It also retains the distinction of being the only such platform with a human crew, which provides unique opportunities and advantages, particularly in the arena of data collection for disaster response efforts. So, what can the space station offer in terms of Earth remote sensing that free-flying, polar-orbiting robotic satellite systems cannot?

Images with a Variety of Lighting Conditions

Unlike many of the traditional Earth observation platforms, the space station orbits the Earth in an inclined equatorial orbit that is not sun-synchronous. This means that the space station passes over locations between 52 degrees north and 52 degrees south latitude at different times of day and night, and under varying illumination conditions. Robotic, satellite-based, Earth-observing sensors are typically placed on polar-orbiting, sun-synchronous platforms in orbits designed to pass over the same spot on the Earth's surface at approximately the same time of day. This paradigm is now changing through the use of smaller platforms (e.g., CubeSats) that allow for multiple installations of the same sensor on multiple platforms in different orbits.

The presence of a human crew that can react to unfolding events in real time, rather than needing a new data collection program uploaded from ground control, provides a unique capability over robotic orbital systems.

Responsive Data Collection

The presence of a human crew that can react to unfolding events in real time, rather than needing a new data collection program uploaded from ground control, provides a unique capability over robotic orbital systems.

This is particularly important for collecting imagery of unexpected natural hazard and disaster events such as volcanic eruptions, earthquakes, flooding and tsunamis. The crew can also determine whether viewing conditions—such as cloud cover or illumination—will allow useful data to be collected, as opposed to a robotic sensor that collects data automatically without regard to quality.

This is well demonstrated by the space station's response to natural hazard and disaster events, in support of the International Charter, Space and Major Disasters (**http://www.disasterscharter.org/home**), also known as the International Disaster Charter (IDC). The space station became a participating platform—in other words, a potential source of remotely sensed data—in April 2012, joining many other NASA satellite assets. As of April 2018, the NASA-managed sensor

systems on the space station have responded to 235 IDC activations, with data collected for 63 of those events by either astronauts or ground-commanded sensors (or both). In addition, the space station participates in the NASA Earth Science Disasters Program (**https://disasters.nasa.gov/**) for response to other disaster-related events that do not require IDC activation.

The following NASA Earth observation instruments and facilities are now aboard and operational on the space station.

The **Window Observational Research Facility** (WORF) provides a highly stable, internal mounting platform to hold cameras and sensors steady while offering power, command, data and cooling connections. Currently, the WORF hosts the Meteor instrument that is obtaining the first space-based observations of the chemical composition of meteors entering Earth's atmosphere. These data will improve our understanding of the processes that formed our solar system.

The **Crew Earth Observations** (CEO) Facility includes Earth imagery taken by crew members using handheld digital cameras. This imagery supports disaster response, scientific investigations by a variety of external Principal Investigators (such as the Tropical Cyclone project), and commercial endeavors under the auspices of the ISS National Laboratory.

The **High-Definition Earth Viewing** (HDEV) camera mission includes four different commercial, high-definition cameras on the Columbus External Facility. This ongoing investigation is assessing camera quality while taking Earth imagery and the hardware's ability to survive and function in the extreme thermal and radioactive environment of low-Earth orbit.

The **Stratospheric Aerosol and Gas Experiment** (SAGE)-III mission investigates the vertical distribution of ozone, trace gases and aerosols in Earth's stratosphere and troposphere. These measurements will improve our understanding of ozone generation and destruction processes in the upper atmosphere, and how climate change is impacting those processes.

The **Lightning Imaging Sensor** (LIS) mission obtains global measurements of the amount, rate and radiant energy of lightning from orbit. This information provides a link between geophysical processes and thunderstorms, thereby improving knowledge of how these interactions affect weather, climate, lightning physics and atmospheric chemistry.

The **Total and Spectral Solar Irradiance Sensor** (TSIS)-1 mission collects data on the sun's energy output. These data increase our understanding of how much energy input the sun provides to the Earth geophysical system, and also how the atmosphere responds to changes in solar output. Such knowledge is critical to improving global climate change models.

The **ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station** (ECOSTRESS) mission thermal infrared sensor that collects data on plant evapotranspiration processes. These data will allow us to monitor how regional plant stress is changing due to global climate change.

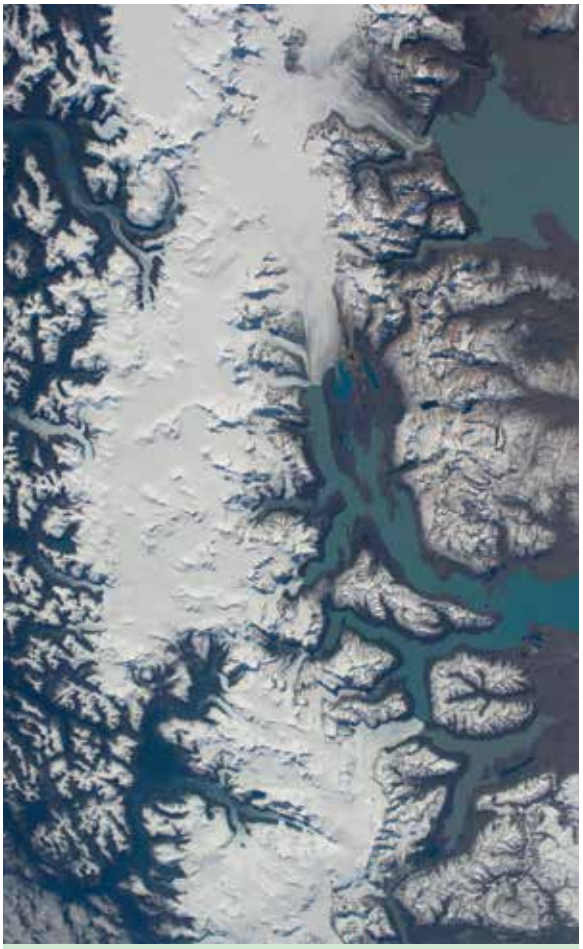


Photo of Patagonian Ice Fields clouds taken by the Expedition 43 crew from the WORF using a zoom lens.

Image credit: NASA

Crew Earth Observations of forest fires near Sydney, Australia, taken with a handheld camera just after local sunset on Oct. 23, 2013. Orange fires and gray smoke threaten nearby towns.

Image credit: NASA

The **Global Ecosystem Dynamics Investigation** (GEDI) mission uses a three-LiDAR system to map global forest vertical structure. This information, compared with historical information on forest canopy structure and extent, helps to characterize and measure the effects of climate change and land use change on the above-ground biomass associated with forest cover.

The combined capabilities of both human-operated and autonomous sensor systems aboard the space station are helping to significantly improve our ability to monitor the Earth's land and water surface and our atmosphere, and to respond to natural hazards and disasters. Integration of the space station Earth observation systems represents a significant and complementary addition to the international, satellite-based, Earth-observing "system of systems," providing knowledge and insight into our shared global environment.

Tracking Global Marine Traffic and Saving Lives

The Vessel Identification System on the Columbus module of the space station has successfully monitored maritime traffic since 2010. This has not only been a successful testing of a system that has shown great improvements in monitoring global maritime traffic, it has proven that the system can save lives.

The current ground-based Automatic Identification System (AIS), as specified by the International Maritime Organization (IMO), is a ship-and-shore-based broadcast system designed to monitor maritime vessels only in coastal waters. The AIS for Columbus, known as the Vessel Identification System, operates in the very high-frequency (VHF) maritime band and greatly expands this capability. This AIS has been

This crucial technology continues to save lives by allowing ships that are close to accidents or emergencies to come to the aid of vessels in distress.

Satellite-Based Receivers Provide Expanded Cover

A partnership between the International Space Station and the Norwegian Defense Institute (FFI) led to the installation of Automatic Identification System (AIS) receivers on the space station, capable of receiving data from vessels throughout the ocean in areas that were previously too remote to detect. The extension of the AIS infrastructure, which prior to implementation on the space station was primarily ground-based and limited to coverage within 15 miles of shore, has led to the proliferation of satellite-based AIS receivers including those onboard the space station. This space-based expanded coverage facilitated rescue efforts for 24 ships sunk, foundered, grounded or otherwise lost at least 15 nautical miles away from shore in 2017 alone—310 passengers and crew members were rescued during these incidents.

verified as a method of tracking global maritime traffic from space and incorporates maritime traffic in open waters. The autonomous system picks up signals from standard AIS transponders that are carried by all international ships over 300 gross tonnes on international voyages, cargo vessels over 500 gross tonnes that are not engaged on international voyages, and all types of passenger ships mandated by the IMO to carry AIS transponders. The space station's location at an altitude of 217 to 248 miles (350 to 400 km) is ideal for space-based AIS signal reception and provides the means to be utilized by multiple users.

During the system's time in orbit, it has not only greatly increased the AIS coverage in open seas, the system has undergone upgrades that further improve its performance, such as in crowded shipping areas where disturbed signals or signal collisions can occur. The Norwegian Automatic Identification System (NORAIS) receiver operated by Norway receives data almost continuously, all modes of operation work well, and near-real-time data delivery became part of routine operations in November 2011. Integrating AIS information with other satellite data, such as that from remote-sensing satellites, should significantly improve maritime surveillance and boost safety and security at sea. The results will support the design and development of a space-based AIS system in general as well as the performance of the AIS receiver on the space station.

The Vessel Identification System could be beneficial to many European entities, particularly law enforcement, fishery control campaigns, maritime border control, maritime safety and security issues including marine pollution survey, search and rescue, and anti-piracy.

Eirikur Johannsson of Norway, for one, is very thankful for the Vessel Identification System on the space station. He owes his life to the system, which tracked the AIS signal of his vessel, the Hallgrimar, when it capsized after an accident. This crucial technology continues to save lives by allowing ships that are close to accidents or emergencies to come to the aid of vessels in distress.

Visual and Instrumental Scientific Observation of the Ocean from Space

One feature of oceanographic research conducted with the participation of cosmonauts on orbital stations (https://www.nasa.gov/mission_pages/station/research/overview.html)—including the historical Salyut and Mir, and the current space station —is the broad application of the method of scientific visual and instrumental observation (VIO) of the world's oceans from space. The basis of this method is the visual search, detection and identification of phenomena under examination in the near-surface layer of the ocean and the atmosphere above it. This is the simplest, yet one of the most informative, ways to obtain data in the visible spectrum on the condition of the ocean's natural environment.

The reliability and scientific value of information on the ocean obtained in this way significantly increases because of the targeted use of special recording equipment (e.g., digital photo and digital video cameras) and onboard instruments that expand the capabilities of the crew member's visual analysis capabilities during observations. Such combined observations are referred to as visual and instrumental. VIO methods are used to establish informational databases in the visible electromagnetic wave spectrum not only in the field of remote sensing of the oceans, but in other areas of knowledge and practical activity.

The many years of Russian experience conducting oceanographic experiments by crews on the long-term, orbital stations—Salyut, Mir and ISS—have made it possible to evaluate the actual informational potential of VIO of the world's oceans. Also, this has allowed for the development of a flight-tested method of solving specific issues of oceanography, and of developing equipment and procedures for the remote sensing of the ocean. These procedures and methods are frequently reviewed while conducting oceanographic experiments with cosmonauts' participation, as is currently done on the space station as part of some space experiments (e.g. Diatomea, Seiner, etc.).

The main object of search and observation for a cosmonaut researcher while working on this category of task using VIO is large-scale, color-contrast formations on ocean surfaces related to the mass growth of phytoplankton (see chart on following page, Image 1). A wide variety of cloud formations are constantly present in the field of view for space station crews observing the ocean surface along the flight path. In addition, the following are observed among cloud fields above the ocean: cloud indicators of tropical cyclones in varying stages of development (Image 2), lineaments (Image 3) identifying jet streams, cumulus clouds with powerful vertical development above the ocean surface under intensive atmospheric convection (Image. 4), and other phenomena of interest for maritime meteorology that serves the shipping, aviation and seafood industries.

Tropospheric cloud formations characteristic of the movement of air masses past obstacles in the atmosphere of island regions (e.g., Karman vortex streets, Helmholtz gravitational shear waves, etc.) are of particular importance among hydro-meteorological phenomena observable by the VIO method. Experiments have also proven the capability to identify and record, through imagery from space, optically active events in the atmosphere—e.g., terrigenous dust and sand flows (Image 13), fog, volcanic ash clouds over the ocean, etc.—and regions with signs of intensive thunderstorm activity. Applicable to the hydro-physical area of oceanic research, the VIO method ensures obtaining documented data on the nature of local water circulation (Image 1), icebergs (Image 6), the structure of surface agitation fields (Images 7 and 8), broken ice (Image 5), and the color and transparency of water (Images 1, 9 and 10). The results of such data interpretation are used to describe the most significant elements of general ocean water circulation, and to deal with hydro-optic tasks.

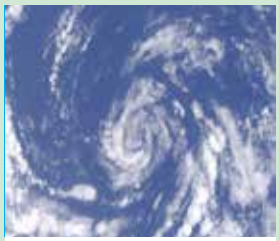
One feature of oceanographic research conducted with the participation of cosmonauts on orbital stations—including the historical Salyut and Mir, and the current space station—is the broad application of the method of scientific visual and instrumental observation (VIO) of the world's oceans from space.

To date, a significant amount of information obtained from the VIOs of the oceans from space has been collected and grouped according to various objects of environmental monitoring. As applicable to open ocean ecosystems, the most broadly represented are the results of observations and color photographs of the ocean characterizing the diversity of forms and condition of coral reefs (Images 11 and 12), the morphology of different sizes of phytoplankton fields, and the hydro-dynamic specifics of the environments in which they live (Image 1).

The most important aspect of the VIO method is the capability to evaluate the environmental condition of the ocean atmosphere system in real time to identify anomalous processes and phenomena in the ocean environment. These processes and phenomena include surfactant films (Image 14), oil and petroleum products spills (Image 16), contamination of clean ocean waters with surface runoff (Image 15), and rinsing agents of ferromanganese nodules mined from the sea floor in mining areas of the oceans.

Currently, VIOs from space have broad practical applications for resolving issues pertaining to the research of biological resources of the world's oceans. The increased attention to this area of research is explained by the relevance of the problem, the capability to conduct research using relatively inexpensive commercial photography equipment, and the existence of an algorithm of searching and identifying highly productive waters of the world's oceans that have been tested by crews on Russian space stations, and subsequently patended.

1. Phytoplankton field

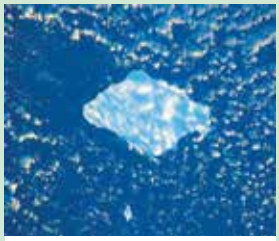


2. Cloud canopy of a typhoon

3. Cloudless lineaments

4. Clouds of intensive vertical development

5. Condition of ice cover



6. Antarctic iceberg

7. Development of internal waves

8. Area of calm in the shadow of an island

9. Sea floor relief

10. Sea floor of Bermuda

11. Sea floor of an atoll

12. Above-water part of an atoll

13. Dust/sand streams

14. Surfactant film contamination

15. River runoff contamination

16. Oil spill

Images of the ocean from space.

Images credits: ROSCOSMOS/Energia/FGUP TsNIIMash

Improving Climate Models on Earth

Climate models are essential in forecasting global changes in Earth's climate and weather, and in determining the role humanity plays in these changes. These models require input parameters. One of the major factors that influences Earth's climate is the sun. Therefore, studying the sun and understanding how it influences Earth has a significant effect on such models.

Climate models are essential in forecasting global changes in Earth's climate and weather, and in determining the role humanity plays in these changes.

The European Space Agency (ESA) Sun Monitoring on the External Payload of Columbus (Solar) facility measured the spectrum of solar radiation over a period of 9 years, ending in 2017, far extending its original planned lifespan of 18 months to 2 years. These measurements generated a wealth of data during the approximately 11-year solar cycle—i.e., a regular period of increasing and decreasing solar activity. These data help scientists better understand and deal with all aspects influenced by solar radiation. The Solar facility data contribute to the understanding of solar and stellar physics and Earth System sciences such as atmospheric chemistry and climatology. Data from the Solar facility have already helped validate improved models of the upper atmosphere, which is important for climate modelling. The data also contribute to improving the accuracy of navigation data, as well as the orbit forecasts of satellites and debris.

The facility undertook significant activities such as performing simultaneous measurements with ESA's Venus Express spacecraft close to the transit of Venus across the sun, thus enabling in-orbit calibration of a Venus Express UV spectrometer. Extended measurements were also performed during an entire sun rotation cycle, which lasts around 26 days at the solar equator and up to 36 days at the solar poles. This produced excellent scientific results.

Microwave Radiometry—Passive Remote Sensing of the Earth in Decimeter Wavelength Range

The thermal radio emission of natural objects in decimeter wavelength range carries important information about their state and, freely penetrating through the Earth's atmosphere, can be received and measured by a special device—a radiometer—at a considerable distance from the objects themselves (e.g., from a satellite). Performing satellite radio-thermal observations allows all-day, all-season and all-weather (i.e. practically independent of the state of the atmosphere) research and monitoring of the environment and its change in planetary scales. Therefore, satellite radiometry is a unique tool for Earth exploration.

In 2011, a space experiment, Microwave Radiometry, was conducted aboard the Russian Segment of the ISS.

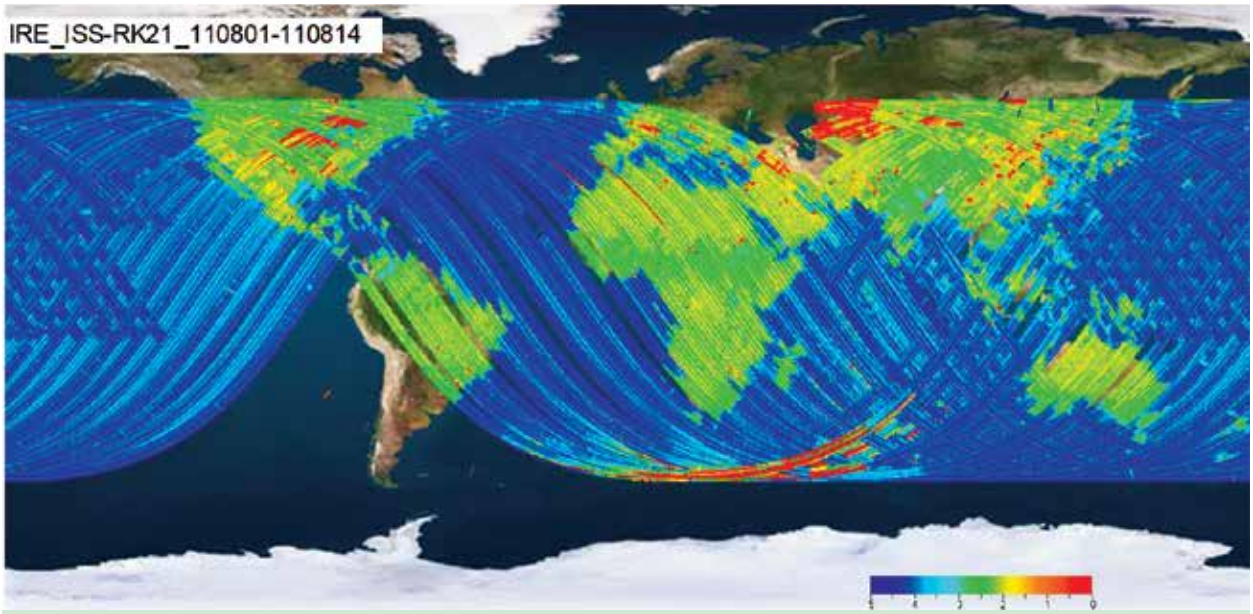
Placement of scientific equipment RK-21-8 onboard the Russian Segment of the ISS.

Image credit: ROSCOSMOS

In 2011, a space experiment, Microwave Radiometry, was conducted aboard the Russian Segment of the ISS. Its purpose was to develop methods for remote sensing of the Earth in the prospective decimeter range of electromagnetic waves to determine the following characteristics of the underlying surface: soil moisture, vegetation cover parameters and sea surface salinity.

A new unique device, RK-21-8—an eight-beam microwave radiometer of the decimeter range—was developed and manufactured to implement the space experiment Microwave Radiometry.

Successful realization of the experiment allowed for the development of methods for remote sensing of the Earth, which will be used to solve problems in ocean physics, climatology, weather forecasting and other applications. The developed methods and technologies for the delivery, installation and operation of scientific equipment on the ISS would be used in succeeding space experiments, as well as for the assembly of prospective space stations.



The Earth in the decimeter wavelength range as observed by RK-21-8.
Image credit: ROSCOSMOS

Disaster Response

Remotely sensed data acquired by orbital sensor systems has emerged as a vital tool to identify the extent of damage resulting from a natural disaster, as well as providing near-real time mapping support to response efforts on the ground and humanitarian aid efforts. The International Space Station (ISS) is a unique terrestrial remote-sensing platform for acquiring disaster-response imagery. Unlike automated remote-sensing platforms it has a human crew; is equipped with both internal and externally mounted still and video imaging systems; and has an inclined, low-Earth orbit that provides variable views and lighting (day and night) over 95 percent of the inhabited surface of the Earth. As such, it provides a useful complement to autonomous sensor systems in higher-altitude polar orbits for collecting imagery in support of disaster response.

Clear High-definition Images Aid Disaster Response

Data collected from various ISS (**https://www.nasa.gov/mission_pages/station/research/overview.html**) sensor systems have contributed to Earth observation and disaster response through international collaboration frameworks such as the International Charter, Space and Major Disasters (**http://www.disasterscharter.org/home**) and Sentinel Asia (**http://www.jaxa.jp/article/special/sentinel_asia/index_e.html**). The Japanese Experiment Module (JEM), or Kibo, provides opportunities to obtain very clear high-definition (HD) images both from internal handheld cameras and from externally mounted cameras. These clear images are beneficial for disaster support.

The Japan Aerospace Exploration Agency (JAXA) offers data taken with two camera systems: the Super Sensitive HD Television (SS-HDTV) Camera System and the High Definition TV Camera - Exposed Facility 2 (HDTV-EF2) mounted on JEM Kibo Exposed Facility (JEM-EF). JEM-EF is an unpressurized, multipurpose pallet structure attached to the JEM. This external platform is used for research in diverse areas such as communications, space science, engineering, technology demonstration, materials processing and Earth observation.

Images of the Earth's surface, oceans, clouds, etc., are taken from the space station for disaster response, education and publicity purposes.

SS-HDTV was developed to take night images of the Earth, including such phenomena as aurora, airglow and meteor showers. It is operated in the ISS pressurized module cabin including the JEM and the Cupola Observational Module. The beautiful night images are utilized for the check of the electric power restoration, the revival of cities after a natural disaster, and the return to normal life for those people affected.

Images of the Earth's surface, oceans, clouds, etc., are taken from the space station for disaster response, education and publicity purposes.

HDTV-EF2 also provides the Earth surface images with 4k high resolution on demand from Sentinel Asia, although its main purpose is to demonstrate that the commercial products can normally operate, for a long period of time, in the space environment. Sentinel Asia aims to promote international cooperation to monitor natural disasters in the Asia-Pacific region. According to statistics by the Asian Disaster Reduction Center's Natural Disasters Data Book 2013, Asia accounts for 44.6 percent of occurrences; 84.6 percent of people killed; 87.1 percent of affected people; and 49.0 percent of economic damage. Under these circumstances, the Asia-Pacific Regional Space Agency Forum proposed Sentinel Asia in 2005 to showcase the value and impact of Earth observation technologies.

Sentinel Asia uses Earth observation satellites and other space technologies to collect disaster-related information, and then shares it over the internet. The aim is to mitigate and prevent damage caused by natural disasters such as typhoons, floods, earthquakes, tsunamis, volcanic eruptions

Wildfire, Queensland, Australia.
Image credit: JAXA/NASA

Hurricane Irma, Atlantic Ocean, September 2018.
Image credit: JAXA

Night view of Italy.
Image credit: JAXA/NASA

Night view, aurora and airglow.
Image credit: JAXA/NASA

Night view of Tokyo, Japan, as seen from the ISS.
Image credit: JAXA

Night view of Buenos Aires, Argentina, as seen from the ISS.
Image credit: JAXA

and wildfires. Sentinel Asia now counts 15 international organizations and 83 participating organizations from 25 countries as members, and utilization of its systems is steadily expanding. JAXA, as the only Asian partner of the ISS, will continue to support disaster response and hopes to contribute to Asia and the whole world with Kibo and its HD cameras.

Transluminous Events Offer Valuable Insight

The methods implemented during the SS-HDTV investigation on the International Space Station have resulted in the ability to study elusive transluminous events (TLEs) in more detail than any existing satellites. An accurate climatic picture of TLEs allows for better disaster prediction and responses.

NASA Explorer Schools 2009 Student Symposium, April 29 - May 1, 2009.

Image credit: NASA

Global Education

The International Space Station has a unique ability to capture the imaginations of both students and teachers worldwide. The presence of humans aboard the space station provides a foundation for numerous educational activities aimed at piquing interest and motivating children toward the study of science, technology, engineering and mathematics. Projects such as the Amateur Radio on International Space Station, Asian Try Zero-G, and Synchronized Position Hold, Engage, Reorient Experimental Satellites Zero Robotics competition, among others, have allowed for global student, teacher and public access to space through student image acquisition and radio contacts with crew members. Projects such as these and their accompanying educational materials are distributed to students around the world. Through the continued use of the space station, we will challenge and inspire the next generation of scientists, engineers, writers, artists, politicians and explorers.

Inquiry-based Learning

Since the launch of the first modules of the International Space Station (ISS) into orbit, students have been provided with a unique opportunity to get involved and participate in science and engineering projects. Many of these projects support inquiry-based learning—an approach to science education that allows students to ask questions, develop hypothesis-derived experiments, obtain supporting evidence, analyze data, and identify solutions or explanations. This approach to learning is well-published as one of the most effective ways in which to engage and influence students to pursue careers in scientific and technology fields.

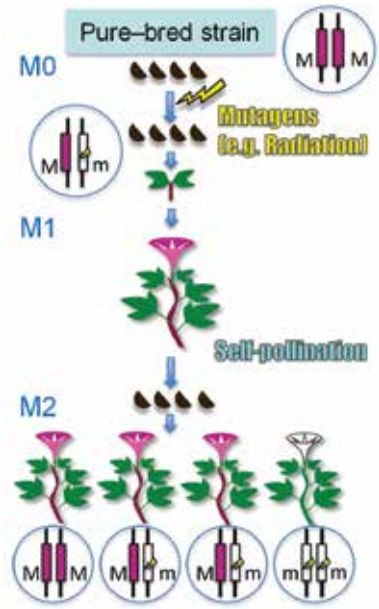
JAXA Seeds in Space

The Japan Aerospace Exploration Agency (JAXA) has encouraged students and teachers to find mutants from specimens including spaceflight plant seeds by learning how to conduct a real scientific investigation. One group of Japanese morning glory (Asagao) seeds was stored on the Japanese Experiment Module Kibo of the space station for nearly 9 months and then returned to Earth. The spaceflight seeds were distributed to schools for the experiment, and included a set of negative-control seeds stored on Earth and a set of positive-control seeds irradiated with carbon ion beams at the RIKEN Accelerator Research Facility. Pure-bred strains of plants with diploid and self-pollination characteristics such as the morning

Students plant morning glory (Asagao) space-flown seeds as part of the JAXA Seeds in Space program. Insets include A: a mutant of M2 Asagao (pigment-deficient); and B: a wild type of M2 Asagao.

Image credit: Dr.Eiji Nitasaka and JAXA

More than 18,000 students and teachers from kindergarten to high school participated in the JAXA Seeds in Space scientific education program from 2010 to 2017.



How to detect and isolate mutants (recessive homozygotes) from a pure-bred strain in the Japanese morning glory (Asagao).

Image credit: Dr.Eiji Nitasaka

glory can be used to identify the mutants from their phenotypes in the M2 generation. More than 18,000 students and teachers from kindergarten to high school participated in the JAXA Seeds in Space scientific education program from 2010 to 2017.

By June 2018, two distinct types of mutant plants had been isolated. One of the plants featured a white flower (a pigment-deficient one). Working together, JAXA's investigators conducted DNA sequencing of the plant genes to try to determine the reasons for the mutation. Upon completion of their study, investigators concluded that the mutant with a white flower was probably not caused by space radiation. However, there is no doubt that all participants—every student and teacher—were thrilled in the experiment to touch something having returned from the spaceflight, and to be the ones to isolate the mutants.

Students Photograph Earth from Space

Sally Ride Earth Knowledge Acquired by Middle School Students (EarthKAM) is a NASA educational outreach program that enables students, teachers and the public to become researchers, with a focus on learning about Earth from the unique perspective of space.

During four missions per year, middle-school students around the world could request images of specific locations on Earth. Accompanying learning guides and activities provided resources to engage students in Earth and space science, geography, social studies, mathematics, communications and art.

In February 2018, the space station crew shut down and stowed EarthKAM; however, the entire collection of Sally Ride EarthKAM images remains available in a searchable image archive. In all, a total of 273 schools representing 21,417 students and 35 countries

Since its first space station expedition in March 2001, Sally Ride EarthKAM has touched the lives of nearly 300,000 student participants and an unknown number of online followers.

One of the photos taken of The Bahamas during the 2013 spring mission.

Image credit: Sally Ride EarthKAM

Two students from Good Shepherd School in Alberta, Canada, participate in Sally Ride EarthKAM.

Image credit: NASA

signed up to request images, 36,801 image requests were submitted, 8,716 images were downlinked, and 8,716 images were posted to the website.

Students at the University of California, San Diego handled requests for the project. The students compiled the requests into a camera control file and, with the help of NASA Johnson Space Center (JSC), uplinked them to a computer aboard the space station. Requests ultimately transmitted to the digital camera, which took the desired images and transferred them back to the space station computer for downlink to the ground. This entire relay process usually completed within a few hours, with the photos available online for both the participating schools and the public to enjoy.

Sally Ride EarthKAM used a Nikon D2Xs digital camera mounted in the Window Observational Research Facility (WORF), which uses the science window located in the U.S. Destiny Laboratory. This window's high-quality optics capabilities allowed the camera to take high-resolution photographs of the Earth using commands sent from students via the online program.

Students and educators continue to use these photos as supplements to standard course materials, thus combining the excitement of the space station experience with middle-school education.

Sally Ride EarthKAM was initiated in 1995 and was originally called KidSat. The KidSat camera flew on three space shuttle flights (STS-76, STS-81 and STS-86) to test its feasibility before moving to the space station and taking the name ISS EarthKAM. In 2013, the program was once again renamed to honor the late Dr. Sally K. Ride, America's first woman in space and the program's creator. Dr. Ride passed away July 23, 2012.

Since its first space station expedition in March 2001, Sally Ride EarthKAM has touched the lives of nearly 300,000 student participants and an unknown number of online followers. The program also has a strong international presence. Educators and others interested in using Sally Ride EarthKAM images can find them online.

Tomatosphere™: Sowing the Seeds of Discovery through Student Science

Home base on the moon. Boot prints on Mars. Visits to asteroids. With the world's spacefaring nations looking beyond the space station to envision human missions to increasingly distant destinations, scientists have already begun to tackle the many challenges of sending humans farther and farther from our home planet. Missions to the space station have made substantial contributions to our knowledge of how the human body adapts to microgravity for 3, 6 or even 12 months; however, taking steps deeper into our solar system will require much longer expeditions. A human mission to Mars, for instance, will likely mean a 6-month journey each way, coupled with a stay of about 18 months on the surface of the planet.

With the world's spacefaring nations looking beyond the space station to envision human missions to increasingly distant destinations, scientists have already begun to tackle the many challenges of sending humans farther and farther from our home planet.

High school students measure the height of tomato plants as part of the Tomatosphere™ experiment extension.

Image credit: Let's Talk Science

Future crews on long-duration missions will need to be self-sufficient to stay safe and healthy. Since carrying 2 to 3 years' worth of food would be expensive and impractical, astronauts will have to grow their own food en route to their destination. Space farming may sound futuristic, but in the closed environment of a spacecraft, plants could make a huge contribution to life-support systems. Not only do plants provide food, water and oxygen, they also recycle carbon dioxide and waste. But how do you grow plants effectively in the radiation-filled environment of space? Which plants are best suited for space missions? What type of seeds would be able to withstand the journey and still germinate? What if we could recruit the next generation of astronauts, scientists and engineers to help solve the problem?

Since 2001, the award-winning Tomatosphere™ program has done just that. An estimated 3 million students in Canada and the United States have helped researchers gather data to address these questions while learning about science, space exploration, agriculture and nutrition. Tomatosphere™ provides students with two sets of tomato seeds: one set that has been exposed to space or space- simulated environments, and one that has not been exposed but serves as a control group for comparison. Without knowing which set is which, students grow the seedlings in their respective classrooms. They measure a variety of information about the tomato plants, the germination numbers, growth patterns and vigor of the seeds. This methodology, known as a "blind study," allows the mystery of the project to be real science for the students. Each class

Chris Hadfield, Canadian astronaut and former commander of the ISS, poses with 600,000 tomato seeds for the Tomatosphere™ project, which returned to Earth with Hadfield in May 2013 after orbiting Earth for 9 months aboard the space station. The seeds will be grown by classrooms across Canada and the United States.

Image credit: Canadian Space Agency/NASA

submits its results to the project website to be shared with scientists who are studying horticulture and environmental biology.

The project's baseline experiment investigates the germination of the seeds; however, supporting materials have been developed to allow educators from Kindergarten to Grade 12 to build on student understanding of a variety of topics, including the science of plants, nutrition, and ecosystems.

This hands-on approach to learning gives students a taste of science and space research. In addition to being rewarded with their very own "space tomatoes" to bring home, students participating in Tomatosphere™ today know that they have each made a personal contribution to assisting space exploration in the future. Perhaps one day, an astronaut biting into a fresh, juicy tomato on the surface of the Red Planet will thank them.

As of 2014, the Tomatosphere™ program operates under two organizations: the Canadian-based Let's Talk Science and the U.S.-based First the Seed Foundation. These two groups provide seeds and education resources to classrooms throughout Canada and the United States. First the Seed Foundation collaborated with the ISS U.S. National Laboratory to send seeds to the space station in 2017.

*Tomatosphere™ partners include the Canadian Space Agency, First the Seed Foundation, HeinzSeed (**http://www.heinzseed.com/new/hs_home.html**), Let's Talk Science, Stokes Seeds (**http://www.stokeseeds.com**), and the University of Guelph (**https://www.uoguelph.ca/**). Learn more about Tomatosphere™ at: **http://tomatosphere.letstalkscience.ca/** (Canada) or **https://www.firsttheseedfoundation.org/tomatosphere/** (United States).*

Asian Try Zero-G 2018: Igniting the Passion of the Next Generation in the Asia-Pacific Region

Six young, nervous students were gathered in front of a press conference room at the JAXA Tsukuba Space Center. The group included Laurentius Christmarines from Indonesia, Hiroki Fujita and Yoshinori Murakami from Japan, Justin Parel from the Philippines, Paul Seow from Singapore, and Swasamon Jaidee from Thailand as the representatives of students from Asian countries visiting Japan to participate in a JAXA space educational program. Only an hour had passed since they had excitedly observed astronaut Norishige Kanai conduct space experiments, based on their own ideas, on Kibo. Once the press conference began, and with ample enthusiasm reflected in their expressions, these young people actively answered a variety of questions posed by reporters.

JAXA runs the Try Zero-G educational program that is intended to help young people and educators learn about the space station and the research conducted there.

JAXA runs the Try Zero-G educational program that is intended to help young people and educators learn about the space station and the research conducted there. This fundamental physics experiment program originally began as a domestic activity that provided a unique opportunity for the public in Japan to participate in part of a space experiment implementation. The activity has drawn public attention to utilization of the space environment since the program started in 2009. For the first attempt, JAXA selected 16 experiments out of 1,597 candidate

Press conference after the Asian Try Zero-G 2018 event at the JAXA Tsukuba Space Center in Japan.

Image credit: JAXA

experiment concepts, and has successfully continued the program ever since.

With the belief that educational activities on the space station serve to benefit all of humanity, JAXA opened the Try Zero-G program to Asia-Pacific nations in 2011 under the framework of the Asia-Pacific Regional Space Agency Forum. This program features the implementation of student-proposed physics experiments on the space station by Japanese astronauts Satoshi Furukawa in 2011, Akihiko Hoshide in 2012, Koichi Wakata in 2014, Kimiya Yui in 2015, and Takuya Onishi in 2016. Eleven countries—Australia, Bangladesh, Indonesia, Japan, Malaysia, New Zealand, Pakistan, The Philippines, Singapore, Thailand, and Vietnam—have joined the Asian Try Zero-G program series.

On February 13, 2018, astronaut Norishige Kanai, who was onboard the space station for Expeditions 54/55, conducted interesting physics experiments under eight themes, including the movement of a paper boomerang, stability of a paper/wooden plane, and behavior of a spinning ring. The students could experience such experiments under a microgravity environment for the first time. In the JAXA Mission Control Room, the 19 prospective scientists from Asian countries were glued to the live downlink screen showing astronaut Kanai's performance, and they enthusiastically communicated with the astronaut. After observing the space experiments conducted in the microgravity environment, the students commented about this unique experience, as follows:

Asian students watching onboard experiments from the JAXA Mission Control Room.

Image credit: JAXA

"The experiments were amazing. Everything in space is so different from what we thought. It was nice to learn about many different experiments and conditions in zero gravity, which could be applied in various fields such as physics and astrophysics. Today's activities at JAXA's Tsukuba Space Center were very exciting. JAXA did a wonderful job showing us how their ground operations support the space experiments. We learned many things through the activities with friends from Asian countries who share a mutual interest in space. We were so inspired!"

Asian Try Zero-G marks a major step for JAXA toward playing a key role in enhancing Kibo utilization among Asia-Pacific nations, and aiming to share the benefits with them.

HUNCH about Student Success in Engineering?

Several young science, technology, engineering and mathematics (STEM) professionals who are entering the workforce right now are likely to have been motivated to enter those fields by the High school students United with NASA to Create Hardware (HUNCH) Program. HUNCH is a nationwide instructional partnership between NASA, high school students and intermediate/middle school students to build cost-effective hardware and soft goods both for use on the space station and for the training of NASA astronauts and flight controllers.

In existence since 2003, the popular HUNCH Program has grown to include 1,750 students in 77 schools across 24 states. Trainees receive a hands-on opportunity that helps them strengthen their skills in STEM.

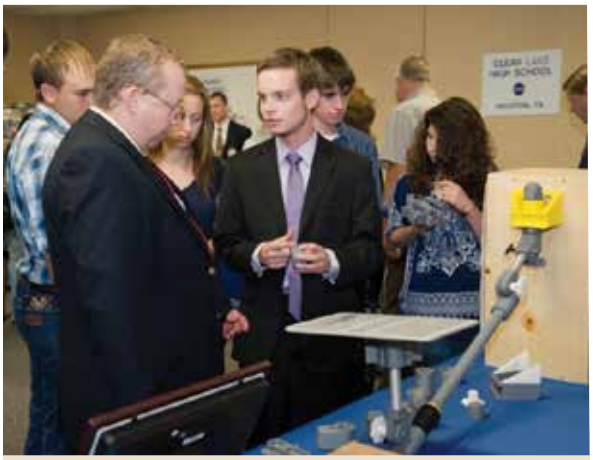
Students that participate in HUNCH learn to use and apply three-dimensional software, drafting, prototyping,

In existence since 2003, the popular HUNCH Program has grown to include 1,750 students in 77 schools across 24 states.

welding, basic architecture, critical-thinking and problem-solving skills. NASA provides materials, equipment, mentoring and inspection oversight during the fabrication of these items. While students are building items for NASA, they are also building their self-confidence and interest as researchers.

To date, HUNCH participants have produced single-stowage lockers, cargo bags, educational videos and experiments proposed to fly on the space station. Some standout projects include the design and fabrication of a disposable, collapsible glovebox; an organizer for crew quarters on the space station; and a European Physiology Modules Rack trainer, which provides facilities for human physiology research. Students produced the cargo bags called Sewn Flight Articles (or Softgoods) as part of a HUNCH Program. These Sewn Flight Articles uses fabric and other soft materials to create goods requested by NASA centers and the space station crew. Since its beginning, HUNCH had produced hundreds of items for NASA.

The HUNCH culinary competition involves students from more than 30 high schools. These students create new dishes, taking into account food processing procedures and nutritional requirements and standards of the JSC Food Lab. Local taste competitions determine the finalists who will compete at JSC, with the winning entree processed by the Food Lab and sent up to the space station for the astronauts to enjoy.



Students from Cypress Ranch High School, Cypress, Texas, present mock-up hardware to staff at JSC. This hardware was built for NASA training programs as part of the HUNCH Program.

Image credit: NASA

In a culmination of skills learned as part of the HUNCH Program, two students from Cypress Woods High School in Texas—Robert Lipham and Alie Derkowski—were selected to attend the Technology Student Association National Competition in Orlando, Florida, to present the skills they acquired while building Microgravity Science Glovebox (MSG) trainers for NASA. HUNCH paired with the ISS U.S. National Laboratory to provide funding for the students to showcase their engineering education endeavors.

Design updates made by Lipham and Derkowski saved NASA money by streamlining the MSG trainers, which are mock-ups of space hardware for crew mission preparation. When the idea to create these items came to HUNCH, the cost estimate was $1 million for four MSG high-fidelity trainers. HUNCH provided NASA with five MSG trainers for less than $250,000.

Every year, recognition ceremonies are held for all students and teachers who participate in the HUNCH Program. The number of participants continues to grow annually, as do the quality, quantity and diversity of products that the students fabricate. Although the recognition ceremonies recognize student work, they also acknowledge the educational benefits of NASA teaming up with students. This is often measured by the changes in the students' attitudes toward their own self-assurance and desire to enter STEM careers.

HUNCH is an innovative solution for inspiring the next generation of researchers and space explorers while providing money savings and resource efficiencies for NASA. Schools can get involved through the online application on the HUNCH website (**http://www.nasahunch.com/**).

Genes in Space-3 Successfully Identifies Unknown Microbes in Space

Being able to identify microbes in real time aboard the ISS without having to send the microbes back to Earth for identification first would be revolutionary for the world of microbiology and space exploration. The Genes in Space-3 team turned that possibility into a reality this year when it completed the first-ever sample-to-sequence process entirely aboard the space station.

The ability to identify microbes in space could aid in diagnosing and treating astronaut ailments in real time, as well as assist in identifying DNA-based life on other planets. It could also benefit other experiments aboard the space station. Identifying microbes involves isolating the DNA of samples, and then amplifying—or making

The ability to identify microbes in space could aid in diagnosing and treating astronaut ailments in real time, as well as assist in identifying DNA-based life on other planets.

many copies of—that DNA, which can then be sequenced or identified.

The investigation was broken into two parts: the collection of the microbial samples and amplification by Polymerase Chain Reaction (PCR), then the sequencing and identification of the microbes. NASA astronaut Peggy Whitson conducted the experiment aboard the space station, with NASA microbiologist and the project's Principal Investigator Sarah Wallace and her team watching and guiding her from Houston.

Petri plates were touched to various surfaces of the space station as part of regular microbial monitoring. Working within the MSG about a week later, Whitson transferred cells from growing bacterial colonies on those plates into miniature test tubes—something that had never been done before in space.

Once the cells were successfully collected, it was time to isolate the DNA and prepare it for sequencing, which enabled the identification of the unknown organisms—another first for space microbiology. A historic weather event, however, threatened the ground team's ability to guide the progress of the experiment.

NASA astronaut Peggy Whitson performed the Genes in Space-3 investigation aboard the space station using the miniPCR and MinION, which were developed for previously flown investigations.

Image credit: NASA

"We started hearing the reports of Hurricane Harvey the week in between Peggy performing the first part of collecting the sample and gearing up for the actual sequencing," said Wallace.

When JSC became inaccessible due to dangerous road conditions and rising flood waters, the team at Marshall Space Flight Center's Payload Operations Integration Center in Huntsville, Alabama, which serve as "Mission Control" for all station research, worked to connect Wallace to Whitson using Wallace's personal cell phone.

With a hurricane wreaking havoc outside, Wallace and Whitson set out to make history. Wallace offered support to Whitson, a biochemist, as she used the MinION device (developed by Oxford Nanopore Technologies) to sequence the amplified DNA. The data were downlinked to the team in Houston for analysis and identification.

"Once we actually got the data on the ground we were able to turn it around and start analyzing it," said Aaron Burton, NASA biochemist and the project's co-investigator. "You get all these squiggle plots and you have to turn that into As, Gs, Cs and Ts."

Those As, Gs, Cs and Ts are Adenine, Guanine, Cytosine and Thymine—the four bases that make up each strand of DNA and can tell you from which organism the strand of DNA came.

"Right away, we saw one microorganism pop up, and then a second one, and they were things that we find all the time on the space station," said Wallace. "The validation of these results would be when we got the sample back to test on Earth."

Soon after, the samples returned to Earth, along with Whitson, aboard the Soyuz spacecraft. Biochemical and sequencing tests were completed in ground labs to confirm the findings from the space station. They ran tests multiple times to confirm accuracy. Each time, the results were exactly the same on the ground as in orbit.

"We did it. Everything worked perfectly," said Sarah Stahl, microbiologist.

This National Lab-sponsored investigation was developed in partnership with JSC and Boeing, and is managed by the Center for the Advancement of Science in Space.

Genes in Space-1 marked the first time the PCR was used in space to amplify DNA with the miniPCR thermal cycler, followed shortly after by Biomolecule Sequencer, which used the MinION device to sequence DNA. Results from the Biomolecule Sequencer investigation were published in Scientific Reports. Genes in Space-3 married these two investigations to create a full microbial identification process in microgravity.

"It was a natural collaboration to put these two pieces of technology together because individually, they're both great, but together they enable extremely powerful molecular biology applications," said Wallace.

Genetic research aboard the space station includes an important educational element: the Genes in Space™ (**https://www.genesinspace.org/**) annual competition. Students in grades 7 through 12 design DNA experiments to send to the space station, with five finalists presenting to a panel of judges at the annual ISS Research and Development conference. The winning team prepares its experiment for launch the following year. The program is supported by a partnership between Boeing, the ISS U.S. National Laboratory, miniPCR, Math for America, and New England Biolabs.

Inspiration

Conducting education activities was not the reason why the International Space Station (ISS) was built; however, the presence of astronauts aboard the ISS serves as an inspiration to students and their teachers worldwide. Connecting with crew members in real time—either through "live" downlinks or by simply speaking via a ham radio—ignites students' imagination about space exploration and its application to the fields of science, technology, engineering and mathematics (STEM).

Inspiring Youth with Science in Space

In the 1960s, widely publicized missions to the moon inspired homemade space helmets and backyard bottle rockets that flew a bit shy of low-Earth orbit. Today, space station education programs inspire the next generation by providing them opportunities to watch, learn from, and even participate in space-based research.

All space station partners—NASA, Canadian Space Agency, European Space Agency, Japan Aerospace Exploration Agency (JAXA) and State Space Corporation ROSCOSMOS (ROSCOSMOS)—lead education projects. These opportunities leverage real research to give students experience with the scientific process.

Past student competitions, including Try Zero-G and YouTube SpaceLab, allowed students to have their experiments performed in orbit. These inquiry-based approaches to learning enabled students and their communities to contribute to the growing knowledge gained from research onboard the space station. Students also gained an understanding of the true nature of science and in-depth knowledge of scientific concepts, laws and theories. The programs helped them develop interests, attitudes and "habits of mind" related to science and mathematics.

Today, ISS education programs inspire the next generation by providing them opportunities to watch, learn from, and even participate in space-based research.

Amateur Radio on the International Space Station (http://www.ariss.org) offers an ongoing opportunity to let students speak directly with astronauts and cosmonauts on the space station via ham radio. These contacts are conducted in voice mode from either the Zvezda Service Module or the Columbus Module. Those conducted in the Columbus Module can be performed via two-way voice augmented with downlink ham video. In-flight education downlink sessions through the NASA Education Office also enable student-crew communications using live video feeds so communities can see the astronauts while speaking with them.

ARISS hardware first launched aboard Space Shuttle Atlantis on STS-106 and transferred to the space station for use by its first crew, and it has been used regularly ever since. ARISS helps to get students interested in STEM by allowing them to talk directly with crew members who are living and working aboard the space station.

An ARISS contact takes place as a part of a comprehensive suite of education activities. To prepare for an exchange, students study the space station and the research conducted there. They also learn about wireless technology, radio science, and satellite communication used for space exploration.

The space station must pass over these earthbound communicators during amateur radio transmissions in order to relay signals between the space station's ham radio and ground receivers. Other factors affect the timing of scheduled contacts, including weather, crew availability, and the schedules of visiting vehicles. These ham radio conversations usually last about 10 minutes. Crew members answer questions from students as they and community members look on. During a pass, the crew can answer an average of 18 questions, depending on their complexity.

Ham radio on the space station connects and inspires students in four ways: providing first-hand education

about life in space, directly connecting students with space station crew, sharing amateur radio technologies, and building global partnerships.

The downlink audio from ARISS contacts can be heard by anyone in range with basic receiving equipment. Transmissions broadcast on 145.800 megahertz. In addition, many contacts now stream live over the internet.

Many different pieces of technology go into a ham radio contact; however, one of the most important is the collaboration between the groups of people involved. Just as the space station is a multinational effort, each ham radio contact requires groups from various cultures, careers and countries to work together.

U.S. educators interested in participating in an ARISS communication can submit a contact proposal during twice-a-year proposal windows. International schools submit applications for consideration via the ARISS website. Submissions are due in July and January of each year.

Since 2000, ham radio has reached 59 countries and more than 1,100 schools or organizations. Overall, education opportunities onboard the space station have involved more than 42 million students, 2.8 million teachers and 25,000 schools.

Another educational opportunity—the Student Spaceflight Experiment Program (SSEP) (**http://ncesse.org/**) in coordination with NanoRacks—provides elementary and middle-school students the opportunity to propose and launch their own investigations to the space station.

For students who have never thought about space exploration, being involved in an amateur radio event can potentially plant the seed of a future career in STEM. From the moon shot to the space station, space exploration continues to inspire the next generation.

Spacecraft and Modern Technologies of Personal and International Communication Links in Education

The Spacecraft and Modern Technologies for Personal Communications (MAI-75) experiment provides real-time video from space. This video is used widely in Russian educational institutions and the international amateur community for the exchange and transmission of information by means of amateur radio communications onboard the ISS. The next stage in the development of the methodology for transmitting

Several dozen receiving radio amateur stations, located on almost all continents, participated in the Inter-MAI-75 sessions of information reception.

different types of information to Earth (i.e., voice, telemetric, black-and-white photos, color photos, video images, and printed text) is the Inter-MAI-75 experiment, which has been implemented onboard the ISS since 2016.

The Inter-MAI-75 experiment involves the methods and specialized software and hardware that were worked out in the MAI-75 experiment. This provides interaction of various categories of users with the ISS crew via specialized communication channels by means of remote user terminals, through the example of the MAI Data Reception and Processing Center and the onboard Sputnik ham radio system. At the same time,

Sample of image taken from the ISS RS in December 2016 by amateur radio communication channel during the sessions of the Scientific Experiment Inter-MAI-75, devoted to the 100th anniversary of the birth of Academician V.P. Mishin.

Image credit: Moscow Aviation Institute (National Research University)

the distinctive feature of the Inter-MAI-75 experiment is to develop methods and tools that ensure the use of information from space for educational purposes, as well as in the overall educational process of the secondary and higher education system. This will make it possible to improve the efficiency of teaching the disciplines of the natural science cycle by attracting students to the real conditions of spacecraft following, as well as to provide additional public attention to the implementation of space programs and opportunities to obtain immediate practical results.

During Inter-MAI-75, the MAI Data Reception and Processing Center, which is equipped with communication facilities with the ISS Russian Segment, and the radio amateurs around the world take images from the ISS. The first experiment sessions attracted widespread international attention. Several dozen receiving radio amateur stations, located on almost all continents, participated in the Inter-MAI-75 sessions of information reception. Data from radio amateurs regarding the reception conditions may be of scientific interest for studying the radio ommunication features of ground receiving stations with space objects in the near-Earth space.

The images received by radio amateurs around the world are posted on the ARISS SSTV gallery (**http://spaceflightsoftware.com/ARISS_SSTV/index.php**).

Sample of image taken from the ISS RS in February 2017 by amateur radio communication channel during the sessions of Scientific Experiment Inter-MAI-75, devoted to the MAI laboratory facilities.

Image credit: Moscow Aviation Institute (National Research University)

Asian Students Work with Astronauts in Space Missions

Methawi Chomthong of Mahidol Wittayanusorn School in Thailand plants chili seeds to observe how they grow, while Leonita Swandjaja of Bandung Institute of Technology in Indonesia distributes tomato seeds to primary school pupils. These seeds have traveled in space, and many students and pupils in the Asia-Pacific region have enthusiastically planted and nurtured these "space seeds." The Space Seeds for Asian Future (SSAF) (**http://iss.jaxa.jp/en/kuoa/ssaf/**) is a joint program run by space agencies and institutions for science education in the region.

SSAF does more than simply send seeds into space and bring them back to Earth. SSAF collaborates between astronauts and students on the ground. In September 2013, astronaut Dr. Karen Nyberg retrieved a box from a stowage rack in the Japanese Experiment Module Kibo. The box contained seedlings of Azuki, small red beans that grew 7 days after being watered and kept under dark conditions.

In parallel on the ground, students prepared their own plant boxes and started cultivating their own seeds. They observed the growth of their plants to identify any difference between the ground and space seedlings. Dr. Nyberg showed the seedlings in the box on a video camera. She then pulled out some seedlings and examined the strength of their stems. The video image of the operation was downlinked to the Tsukuba Space Center, JAXA, Japan. Members of the ground staff observed the space seedlings as conveniently as if they were side by side with her. These downlinked video images were distributed to the organizations that were participating in the SSAF2013 program, and a timeline was set for showing the video to students, thus making them feel as if they were working with an astronaut.

In Malaysia, the National Space Agency (ANGKASA) held a competition to help students develop their

> Students understood the wonderful capability of such tiny seeds by witnessing that they were able to adjust to various gravitational conditions.

Students from Osaka City University, Osaka, Japan, monitor the SSAF2013 experiment at Tsukuba Space Center as members of the ground crew who have played an important role in developing the experiment protocol and preparing the plant materials.

Image credit: JAXA

Malaysian students set up their experiment.

Image credit: MARA Junior Science College, Royal Malaysian Police, Kulim, Malaysia

Students Study Seeds Flown in Space

Students participating in SSAF2013 compared seeds exposed to the microgravity environment on the space station to those in ground controls. The students observed that the growth rate of space station seeds was initially greater than ground controls; however, no significant difference was noted once the plants reached maturity.

skills in science research with SSAF2013. A total of 79 teams, each consisting of five members from 25 primary schools and 54 secondary schools, participated in the competition. In other countries, including Australia, Indonesia, Japan, New Zealand, Philippines, Thailand and Vietnam, various age groups of students learned the scientific method through this experience. These young people play an important role not only in space technology, but in other fields of science and technology for the future development of those areas.

The results showed that the seedlings in space looked quite different from those on the ground. Students understood the wonderful capability of such tiny seeds by witnessing that they were able to adjust to various gravitational conditions. Although stricter control of experimental conditions is required for the more-involved science, the observations in SSAF2013 still offer many hints to scientists who are developing their new research projects.

Students Study Macroparticles in Microgravity (Space Experiment "Coulomb Crystal")

During the last few years, the Space Experiment Coulomb Crystal (CC) has been conducted aboard the Russian Segment of the ISS for the purpose of studying the properties of structures of the like-charged particles. Space Experiment CC is aimed at conducting demonstrations as well as educational and scientific experiments on Coulomb structures of strongly interacting macroparticles in microgravity.

Space Experiment CC demonstrated, for the first time, that it is possible to form stable, spatially ordered structures of several thousand charged particles in a magnetic trap in microgravity to visually observe the processes occurring in them and to study, on their example, the properties of Coulomb systems.

Unlike numerous experiments with dusty plasma, where negatively charged particles are held in electrostatic traps, charged diamagnetic particles are retained in the CC by magnetic forces in a cusp magnetic trap. The main idea of the experiment is that the forces of interaction between particles and the forces holding them in a trap must be of a different nature so that the change in some does not affect the others. The cusp magnetic trap is created by two coaxial electromagnets with oppositely circulating currents in their coils. With equal currents in the coils, a "magnetic well" for diamagnetic particles appears between them. Graphite particles with the highest diamagnetic susceptibility from all known materials are used in the experiment. The charging of particles was carried out through the particle contact with a central wire electrode located along the symmetry axis of the system. In this case, the charge of particles could be of any sign, unlike the case of dusty plasma, where it is always negative. Unlike plasma-dusty structures, the proposed method makes it possible to form stable spatial structures of charged particles in electric discharges, both in a non-ionized gas of various densities and in a vacuum. When the current was changed in one of the coils, a dynamic effect was exerted on the cluster formed by the particles. According to the response of the cluster to this influence, some properties were determined, both in the cluster itself and in the cusp magnetic trap. Depending on what was included earlier—the current in the coils of the electromagnet (i.e., magnetic field) or the potential at the central electrode—the shape and structure of the cluster turned out to be different. In several series of recent experiments, the cluster was destroyed by feeding a sufficiently large potential to the central electrode to overcome the magnetic confinement forces of the particles and the auto-adhesive bonding forces between the particles upon their contact. Contact between particles could occur if the magnetic field was switched on before the potential at the central electrode. In this case, assumptions were made about the structure of the central electrode based on data regarding the nature of the cluster destruction, with a gradual increase in the potential of the central electrode. According to these data, the cluster can consist mainly of filamentary chains located from the central electrode to the periphery and occupying about 10% of its volume, and its charge will be concentrated on the outer shell.

Space Experiment CC demonstrated, for the first time, that it is possible to form stable, spatially ordered structures of several thousand charged particles in a magnetic trap in microgravity to visually observe the processes occurring in them and to study, on their example, the properties of Coulomb systems.

Students and postgraduates of the Joint Institute for High Temperatures of the Russian Academy of Sciences (JIHT RAS) and Moscow Institute of Physics and Technology (MIPT) were involved in all stages of preparation and implementation of the experiment, as well as analysis of the data. The results obtained during Space Experiment CC formed the basis of two Ph.D. theses.

Cosmonaut Gennady Ivanovich Padalka performs the Space Experiment CC.

Image credit: ROSCOSMOS

MAI-75 Experiment, Main Results and Prospects for Development in Education

The MAI-75 experiment develops and validates the concepts for designing and operating an innovative telecommunication satellite system at the Moscow Aviation Institute (MAI) to support video information broadcasting from space in real-time to a wide range of users within Russia's academic mobile communications and internet user communities.

The MAI-75 space experiment ("Spacecraft and Modern Personal Communication Technologies") has been carried out on the ISS Russian Segment (RS) since 2005.

The MAI-75 experiment is carried out using a notebook computer on the ISS RS, which stores and prepares the photos and videos that are then transmitted to Earth using the ham radio communication system, the primary component of which is the onboard Kenwood TM D700 transceiver of the "Sputnik" ham radio system within the 144-146/430-440 MHz bands.

Space experiments such as these enable the secondary- and higher-education systems to enhance the effectiveness of teaching natural sciences and to promote the interest of the public in the space programs implementation.

Russian Cosmonaut M. V. Tiurin during a communication session with the Moscow Aviation Institute.

Image credit: Moscow Aviation Institute (National Research University)

The experiment used a communication channel operated on the ham radio frequencies, allowing for significant expansion of the number of experiment participants both in Russia and globally. The experiment results can be obtained at a work station. All that is needed is transceiver equipment that operates on VHF ham radio frequencies.

During the experiment, a total of 120 communication sessions were carried out between the ISS RS and the MAI Data Reception and Processing Center, each with a duration of 9 to 15 minutes, and more than 240 video images were received. The images ranged in size from 14 KB to 94 KB.

Samples of images taken from the ISS RS by amateur radio communication channel during the sessions of SE MAI-75.

Image credit: Moscow Aviation Institute (National Research University)

After pre-processing, the images obtained are posted on a special website where they can be viewed, reviewed and processed by both educational program participants and common users. Besides the MAI Data Reception and Processing Center, the following were involved in the imagery reception process: Reception centers at higher education institutions in Moscow (M. V. Lomonosov Moscow State University, N. E. Bauman Moscow State Technology University); Krasnoyarsk (Siberian State Aerospace University); and Kursk (Kursk State Technology University); Reception centers at the Aerospace Technology Research Laboratory (Kaluga) of the Russian Defense Sports-Technology Organization; Gagarin Research and Test Cosmonaut Training Center (Star City); and S.P. Korolev RSC Energia (Korolev); Ham radio reception stations in Russia, Western Europe, Central America and Southeast Asia. Some of the video images received are posted on the following site: **http://www.issfanclub.com/image/tid/54**.

During ground-based preparations for MAI-75 experiment sessions, the MAI teachers and students, in conjunction with experts from RSC Energia and FGUP TsNIIMash, led the development and testing of in-orbit procedures and cosmonaut training; the development of software and hardware packages for use on Earth at global test sites and in space; and the development and verification of procedures and tests between the ground-based remote user terminals.

As a result of the first phase of the MAI-75 experiment, students were able to immerse themselves in real-life science and engineering applications, while learning management and leadership skills unique to the space station vehicle.

Space experiments such as these enable the secondary- and higher-education systems to enhance the effectiveness of teaching natural sciences and to promote the interest of the public in the space programs implementation. The capabilities of modern information and communication technologies,

Centers of data reception from the ISS RS during MAI-75 experiment sessions.
Image credit: Moscow Aviation Institute (National Research University)

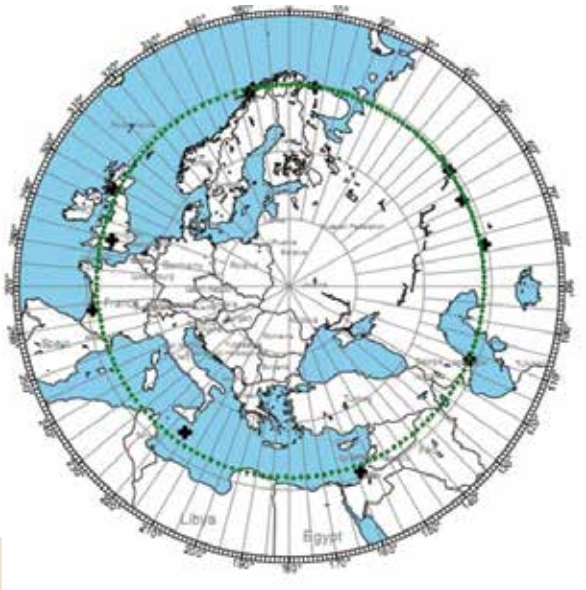
particularly the Internet, and of the mobile (cellular) communications operators enable education program participants to work directly with the general-purpose video equipment deployed on the ISS. Using a Web interface and a special site, the program participants are able to control a digital camera installed on the ISS RS, based on both the Web-posted camera operation schedules and the ISS sub-satellite point movement data.

Educational Benefits of the Space Experiment Shadow-beacon on the International Space Station

The use of spaceflight for stimulation of public interest to advance science and education is a common practice among the global space agencies. The space experiment Shadow-beacon has been performed in series on the RS ISS since 2011 for the scientific and educational purposes.

As an onboard radio beacon transmits VHF sounding signals of a 145-megahertz range, ground participants can register moments of signal appearance, follow the signal until it vanishes using the time marks, and send this information, along with data on its geographical position, to the Information Storing Center on Earth. Every operating sequence would take up to 20 minutes while the ISS is passing over the given continental measuring field.

Expanding the ISS educational laboratory to orbital heights through use of programs such as Shadow-beacon provides opportunities to stimulate student interest and participation in the educational process.



A typical result of construction of ISS experimental footprint contour on the Earth surface in the azimuthal projection.

European measuring field, 27.11.11. Current moment 05.02.23 UTC. Position of under-satellite point: Ukraine, latitude 50.45, longitude 26.54.

Image credit: FGUP TsNIIMash

Onboard amateur radio equipment Sputnik.

Image credit: FGUP TsNIIMash

These data provide instant mutual position of the ISS, and each receiver allows definition of experimental borders of the space station's footprint; i.e., "illuminated" spot on the Earth's surface. With many ground receivers, Shadow-beacon simulates a "multi-beam" method of radio sounding of under-satellite space. Its basic properties are evaluated by comparing obtained experimental and calculated contours of the ISS footprint.

Shadow-beacon is a developing methodology for the future experiment Shadow, which will use radio waves scattering in an artificial plasma.

Possible application of this radio-sounding method is observation of interference in radio communication caused by plasma plumes of perspective electric thrusters, which are planned to be used for Martian expeditions. Exclusive simplicity of the radio-sounding method allows the opportunity to carry out Shadow-beacon by nonprofessional operators (i.e., radio amateurs) and includes participation by educational programs. Therefore, the goals and objectives of the Shadow-beacon are both scientific and educational in nature.

Observations gained in Shadow-beacon sessions using the in-orbit Sputnik hardware between 2011and 2013 involved around 70 ground operators in the testing and development of special software for construction of experimental ISS footprint contours on the Earth's surface. In a November 2011 series of Shadow-beacon sessions, laboratory curriculum for students was tested, and students demonstrated the Shadow-beacon procedure as an extracurricular activity.

For more information about the formulation and conditions of the experiment, the sessions schedule, registration instructions, information on the progress of its implementation, or for training materials, visit the website at **http://knts.tsniimash.ru/shadow/en/Default.aspx.**

To date, the Shadow-beacon website has received more than 160 applications for participation from private and club amateur radio stations. This includes educational institutions interested in using Shadow-beacon procedures in the learning process. To improve the methodology for educational purposes and to strengthen its social significance, the developers hold classes in which students are directly involved in the process of data registration and analysis, and in preparing and sending resulting reports to amateur radio operators. These operators are registered participants of the experiment who will be invited to help the neighboring schools conduct space lessons.

Expanding the ISS educational laboratory to orbital heights through use of programs such as Shadow-beacon provides opportunities to stimulate student interest and participation in the educational process.

Students from Moscow's Center of Social Aid to family and Children "Pechatniki" take part in registration of sounding signals from orbit by field station ra3awc in the November 2011 series of Shadow-beacon.

Image credit: FGUP TsNIIMash

Link to Archived Stories and Videos

http://www.nasa.gov/stationbenefits

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Economic Development of Space

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Principal Investigator (PI) listed for stories focused on a specific space station investigation.

Economic Development of Space

Enabling Commercial Launch Providers

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Finding the Keys in Space to Treat Diseases on Earth

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Company: PeptiDream

Managing the International Space Station National Lab

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A New Approach to Radiation Hardening Computers

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PIs: Eng Lim Goh and Hewlett Packer Enterprises

Commercial Partners Expanding International Space Station Research Capabilities

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Companies: NanoRacks LLC, BioServe

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Small Business Makes Big Strides in Commercialization of Low-Earth Orbit

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The Commercial Multi-use Variable-g Platform

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Company: Techshot

Mixing Up Better Products in Microgravity

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Tropical Cyclone in Sight

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Keeping an Eye on Algae from Space

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Innovative Technology

More Efficient, Lightweight Water Filtration Technologies in Space and on Earth

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Advanced NASA Technology Supports Water Purification Efforts Worldwide

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Space Station-Inspired mWater App Identifies Healthy Water Sources
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Commercial Applications from Microbial Filtration in Space
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Space-tested Fluid Flow Advances Infectious Disease Diagnoses
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Improved Oil Exploitation Strategies
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Improved Industrial Casting Models and Casting Processes
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Clothes "Made In Space"
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Sleepwear with a Purpose
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Three-dimensional Bioprinting in Space
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Beyond the Cloud: Data Processing from Low-Earth Orbit
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Human Health

Space Station Robotic Arm Has a Long Reach
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Robotic Arms Lend a Healing Touch
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Robots from Space Lead to One-stop Breast Cancer Diagnosis Treatment
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Improved Eye Surgery with Space Hardware
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The Art—and Science—of Detecting Chromosome Damage
Author: Jenny Howard
PI: Edwin Goodwin

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Non-invasive Collection of Saliva Helps Monitor Stress Levels in Real Time
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Author: ESA
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Early Detection of Immune Changes Prevents Painful Shingles in Astronauts and in Earthbound Patients
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Cancer-targeted Treatments from Space Station Discoveries
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Space Cardiology for the Benefit of Health Care

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Dressing Astronauts for Return to Earth

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New Technology Simulates Microgravity and Improves Balance on Earth

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Countering Neurological Maladaptation

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New Ways to Assess Neurovestibular System Health in Space Also Benefits Those on Earth

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Space Research Leads to Non-pharmacological Treatment and Prevention of Vertigo, Dizziness and Equilibrium disturbances

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Earth Observation and Disaster Relief

Earth Remote Sensing from the International Space Station

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Tracking Global Marine Traffic and Saving Lives

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Visual and Instrumental Scientific Observation of the Ocean from Space

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Clear High-definition Images Aid Disaster Response

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Global Education

JAXA Seeds in Space

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Tomatosphere™: Sowing the Seeds of Discovery through Student Science

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Asian Try Zero-G 2018: Igniting the Passion of the Next Generation in the Asia-Pacific Region

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HUNCH about Student Success in Engineering?

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Genes in Space-3 Successfully Identifies Unknown Microbes in Space

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Inspiring Youth with Science in Space

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Spacecraft and Modern Technologies of Personal and International Communication Links in Education

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Asian Students Work with Astronauts in Space Missions

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Students Study Macroparticles in Microgravity (Space Experiment "Coulomb Crystal")

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MAI-75 Experiment, Main Results and Prospects for Development in Education

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