IAC-18.B3.3.3

Updated Benefits for Humanity from the International Space Station

International Space Station Program Science Forum*[1]

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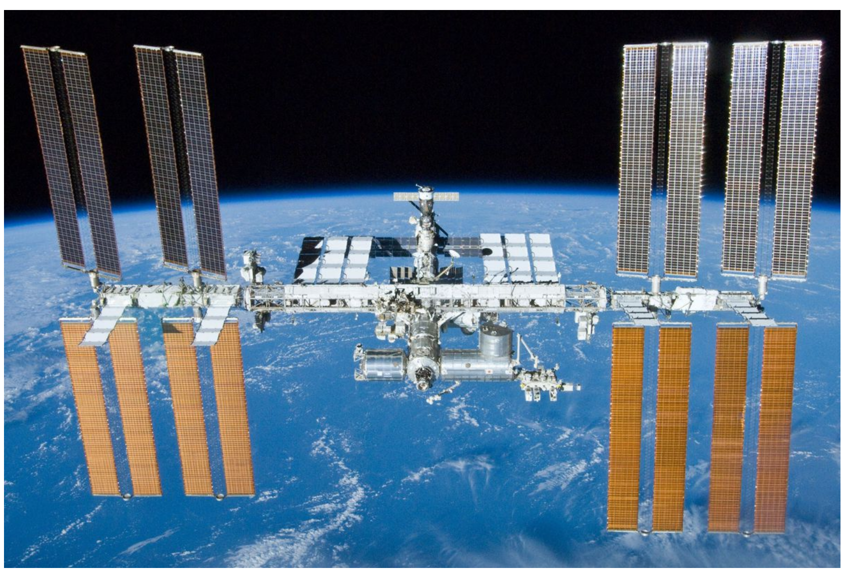

Fig 1. The International Space Station (Image credit: NASA)

Abstract

In 2018, the International Space Station (ISS) [Figure 1] partnership completed a revision for the third edition of the International Space Station Benefits for Humanity, a compilation of case studies of benefits being realized from ISS activities in the areas of human health, Earth observations and disaster response, innovative technology, global education, and economic development of space. The revision included new assessments of economic value and scientific value with 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. This presentation will summarize the updates on behalf of the ISS Program Science Forum, which consists of senior science representatives across the ISS international partnership.

An independent consultant determined the economic valuation (EV) of ISS research benefits case studies and the third edition contains the results. The process involved a preliminary assessment of economic, social, and innovation factors. A more detailed assessment followed, which included factors such as addressable market, market penetration, revenue generation, ability to leverage across other applications or customer groups, quality of life improvements, health benefits, environmental benefits, cultural and community cohesion, inspiration, new knowledge, novel approaches, creation of a unique market niche, and research leadership.

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, analyzing ISS scientific impacts is an exceptional challenge. As a result, the ISS partnership determined the scientific valuation (SV) of ISS research using a combination of citation analyses, bibliometrics, and narratives of important ISS utilization results. Approximately 2,100 ISS results publications comprised of scientific journal articles, conference proceedings, and gray literature, representing over 5,000 authors and co-authors on Earth were used in this evaluation to enable the communication of impacts of ISS research on various science and technology fields across many countries.

The publication also updates and expands the previously described benefits of research results in the areas of space commerce, technology development, human health, environmental change and disaster response, and education activities. It highlights the diversity of benefits from activities on the only orbiting multidisciplinary laboratory of its kind. The ISS is a stepping-stone for future space exploration while also providing findings that develop low Earth orbit as a place for sustained human activity and improve life on our planet.

Keywords: NASA, PSF, ISS, benefits, humanity, science value, research program, human spaceflight

1. Introduction

By challenging human ingenuity to live and work in new extreme environments, space exploration requires innovation, which results in discovery. Innovation creates new technology and discovery results in new knowledge, and both of these create economic opportunity.

The International Space Station (ISS) is a unique scientific platform that so far has enabled researchers in 103 countries and areas to conduct more than 2,600 experiments in microgravity. In the third edition of the *International Space Station Benefits for Humanity* [1] [Figure 2] publication, the scientific and socio-economic impacts of these activities are presented to the global community.

The existence of the ISS has supported a continuous human presence in space since November 2, 2000. The tremendous value of the ISS began through the engineering achievement. Components were built in various countries around the world, many without the benefit of prior ground testing. This process allowed us to vastly increase the global knowledge about multilateral coordination of design, integration, and construction. This mutually beneficial collaborative teamwork is maybe one of the most striking benefits of the ISS. While each ISS partner has distinct agency goals for research conducted [Figure 3], a unified goal exists to extend the knowledge gleaned to benefit all humankind.

In addition to the engineering and international cooperative achievements, the space station is also a stepping-stone for future space exploration, as well as a catalyst for the commercialization of space.

In the first edition of the book [2], released in 2012, the scientific, technological, and educational accomplishments of ISS research that impact life on Earth were summarized through a compilation of stories primarily in three areas: human health, Earth observations and disaster response, and global education. The second edition [3], 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 (EV) and scientific valuation (SV) of space station research.

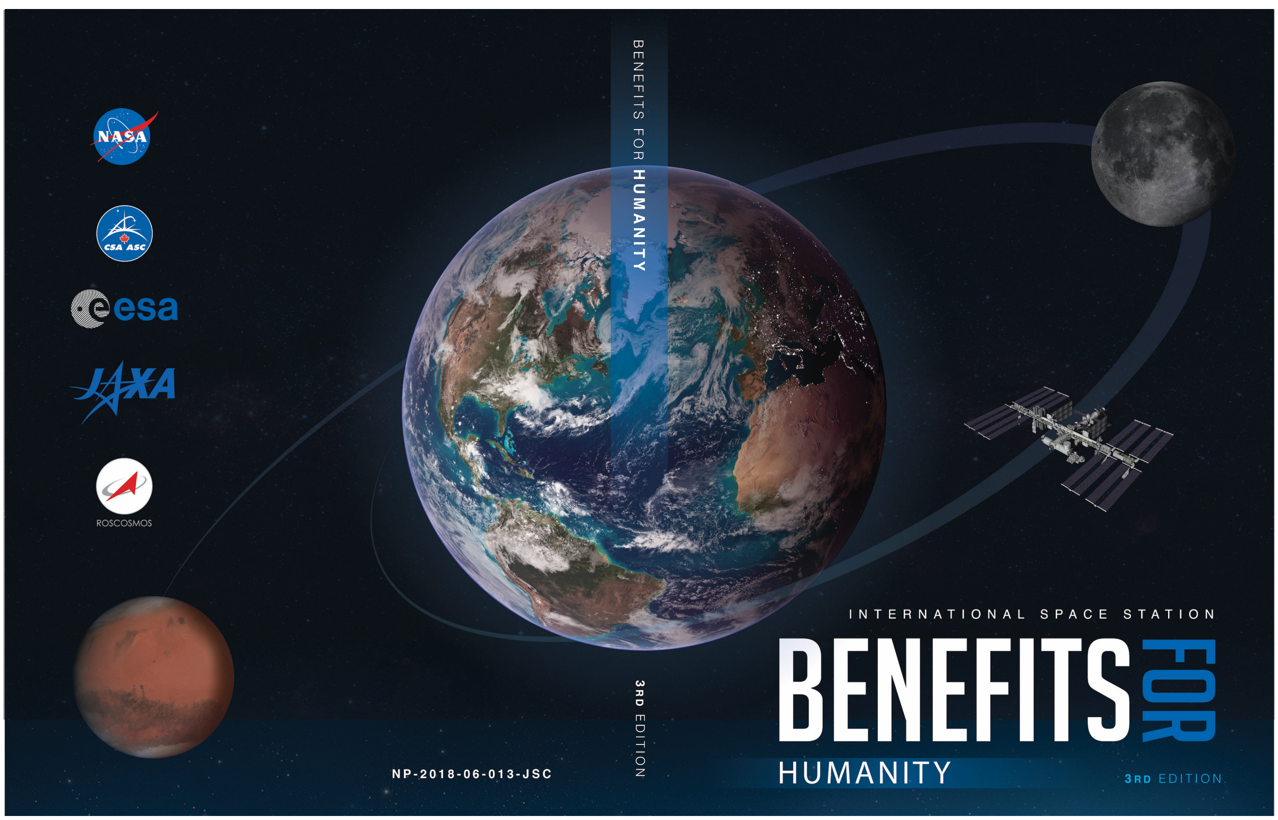

Fig 2. International Space Station Benefits for Humanity 3rd edition Cover (Image credit: NASA)

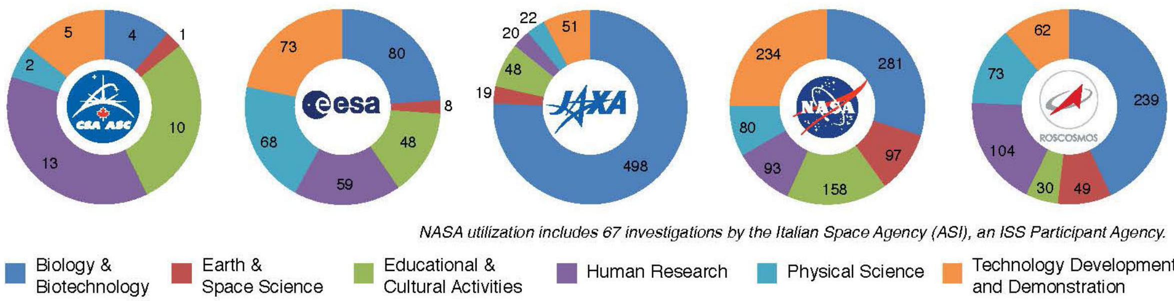

Fig 3. Research Disciplines by Partner Agency: Expeditions 0-54, Dec 1998 – Feb 2018

2. 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 station activities are already entering the marketplace and benefiting lives on Earth. Using research conducted by Navigant Consulting, Inc., the Economic Valuation (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 station has played in nurturing the growing space economy and the increasing interest in space by the private sector.

The global space economy has grown significantly over the past decade, from a valuation of $176 billion in 2006, to a current estimate of $345 billion [4]. The private sector's growing interest in space endeavors is demonstrated by the growth in venture capital investment. From 2000-2014, space start-up companies received a total of $1.1 billion in venture capital investments. [5] In 2015 alone, $1.8 billion was invested, and in 2017, investors reportedly contributed $3.9 billion [6] into commercial space companies.

To characterize the impact of the ISS to date, Navigant Consulting, Inc. applied a value impact methodology customized for space research based on best practices across federal laboratories, commercial companies, and leading nonprofit research organizations. Navigant has prior experience evaluating the potential value impact of proposed space research and has employed this methodology for the research selection process of the ISS National Lab, which is managed by the Center for the Advancement of Science in Space (CASIS).

2.1 ISS Contributions to the Emerging Space Economy

2.1.1 Space Access

The commercial launch market has benefitted 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.

Both COTS and CRS were designed as a demonstration of a public-private partnership model using a fixed-price pay for performance structure, and the results have been decidedly positive. Both SpaceX and Orbital ATK, the two currently active commercial transportation providers, financed over half of the development costs for their systems. 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. [7] 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 pounds, would cost under $700 per pound to LEO. [8] 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.

Results to date indicate that both COTS and CRS have had the positive impact to the space launch marketplace intended. Advances in the commercial sectors ability to provide cargo and crew transportation services to low Earth orbit (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 U.S., growing from a $100 million investment in 2002, to a valuation of over $27 billion in 2018. [9] Orbital Sciences Corporation grew in annual revenue from $676 million in 2006 [10] to $1.37 billion in 2013 [11] - prior to merging with Alliant Techsystems to form Orbital ATK in 2015. Orbital ATK was purchased by Northrup Grumman in 2018 for $7.8 billion and rebranded as Northrup Grumman Innovation Systems [12].

2.1.2 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 (of civil servant workforce and aerospace companies under traditional contracts) 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 procurement approaches such as the Research, Engineering, Mission Integration Services (REMIS) Contract allow for commercial payload and integration providers on ISS.

Commercialization objectives are diverse, with some of the most important being to drive future revenues, market/segment growth, higher levels of employment, and 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 scientific, economic, social, and innovation outcomes.

2.1.3 ISS Role in Small Satellite Market Development

SmallSats (satellites less than 600 kg) [13] offer many advantages over their large, conventional counterparts, including simplified development, relative ease of construction and testing, and lower launch costs. One type of SmallSat, the CubeSat, is defined by specific standards (10 x 10 x 10 cm) and represents 87% of all SmallSats launched as of 2017. [14] By providing opportunities for technology demonstrations and proof-of-concept missions, the space station has helped to mature the capabilities that have triggered rapid growth in the numbers of CubeSats deployed in Earth orbit. Prior to ISS involvement, less than 50 CubeSats had been deployed. Since the first ISS deployment in 2012, annual CubeSat launches have increased by 66% each year. From 2012 to 2017, over 700 CubeSats were deployed worldwide, [14] with approximately 200 being deployed from the space station. Maturation of capabilities, as well as the unique availability of the ISS as a testbed and deployment platform, has continued to attract commercial entities. In 2017, 67% of all SmallSats were developed to provide commercial services. [14]

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. By demonstrating its ability to provide snapshots of the Earth at a useful resolution of 3-5 meters on a daily basis using a fleet of CubeSats deployed from the ISS, Planet was able to enter the marketplace two years earlier than planned. In 2018, with an estimated annual revenue of $64.4 million [15] and value of over $1 billion [16], Planet currently operates a fleet of over 175 satellites and employs over 470 people. [15]

Planet no longer utilizes the ISS. Planet has moved to commercial launch providers to expand its services and constellation of satellites. Not only has the Earth-imaging technology matured, but the business model has proven viable without further ISS involvement, as a new market for medium resolution (3-5 meter) photography from LEO is quickly developing.

And where once SmallSats were the exclusive domain of research institutes and universities, today, 51% of SmallSats are being developed by the private-sector. [17] 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 incubator for experimentation and economic growth.

3. Scientific Valuation (SV)

The international and multidisciplinary nature of the research on 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, and results publications are continuously updated and posted at http://www.nasa.gov/stationresults. As of May 1, 2018, the ISS Program identified 2,135 publications since 1998 with sources in journals, conferences, and gray literature [Figure 4], though there are inherent limitations in also identifying ISS results publications that are published in non-English. After years of evaluating ISS scientific results in many different ways to determine its impacts on the world, one pattern remains clear: space station research has a large global and interdisciplinary impact on scientific advancement.

One method used to evaluate scientific output from

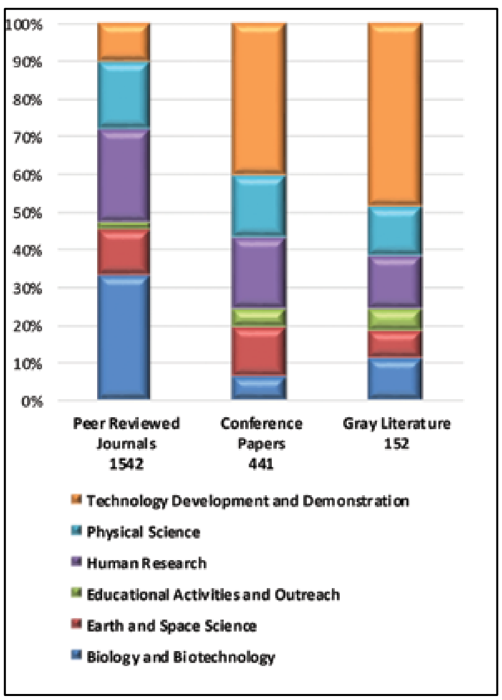

Fig 4. ISS Publications Collected Through May 31, 2018

the ISS is to track the article citations and Eigenfactor® rankings of journal importance across the ISS partnership.

The Eigenfactor® Score is a metric of ranked importance created for each journal based on its influence within complex citation networks and adjusted for differences in discipline, among other factors (www.eigenfactor.org). The score is created from an algorithm that uses Clarivate Analytics' Web of Science citation network, which provides detailed information for more than 8,000 journals in the sciences and social sciences. As of May 2018, 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 ® [Figure 5].

ISS Publications in the Top 100 Global Journals, by Eigenfactor

	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)

Fig 5. ISS Publications in the Top 100 Global Journals, by Eigenfactor, as reported by 2016 Journal Citation Reports®

3.1 Characteristics of Space Station Science

3.1.1 Space Station Science is Global

Space station research also affects scientific advancement beyond the countries whose agencies sponsored them. The heat map [Figure 6] provides a global representation of all 112 countries whose scientists have cited ISS results published in scholarly

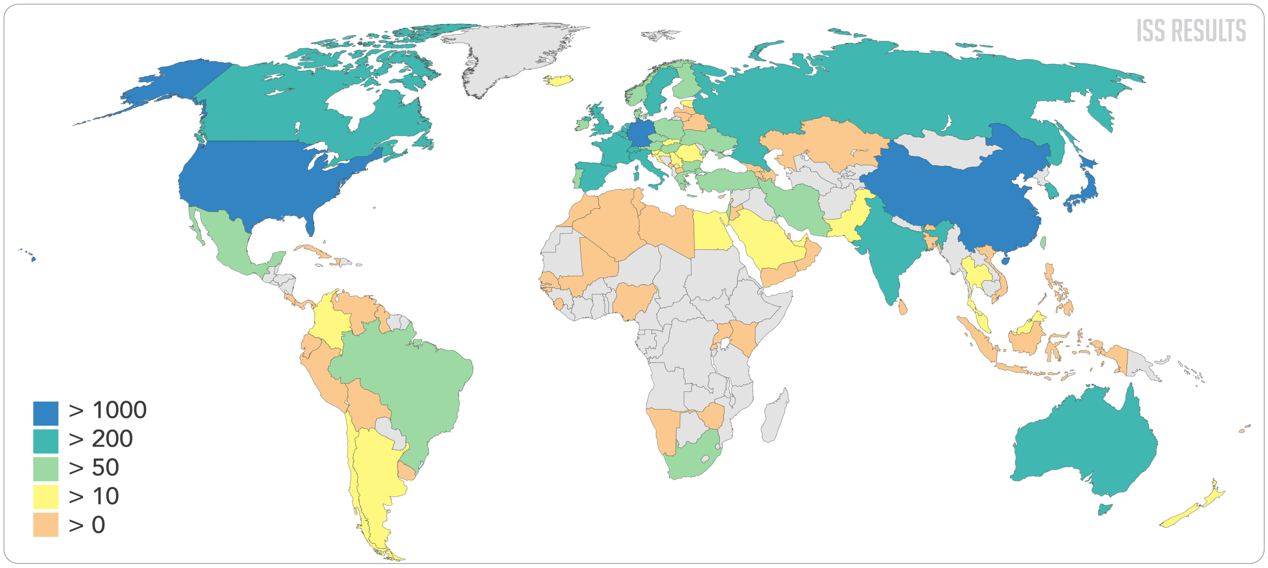

Fig 6. Heat Map of All ISS Results Citations

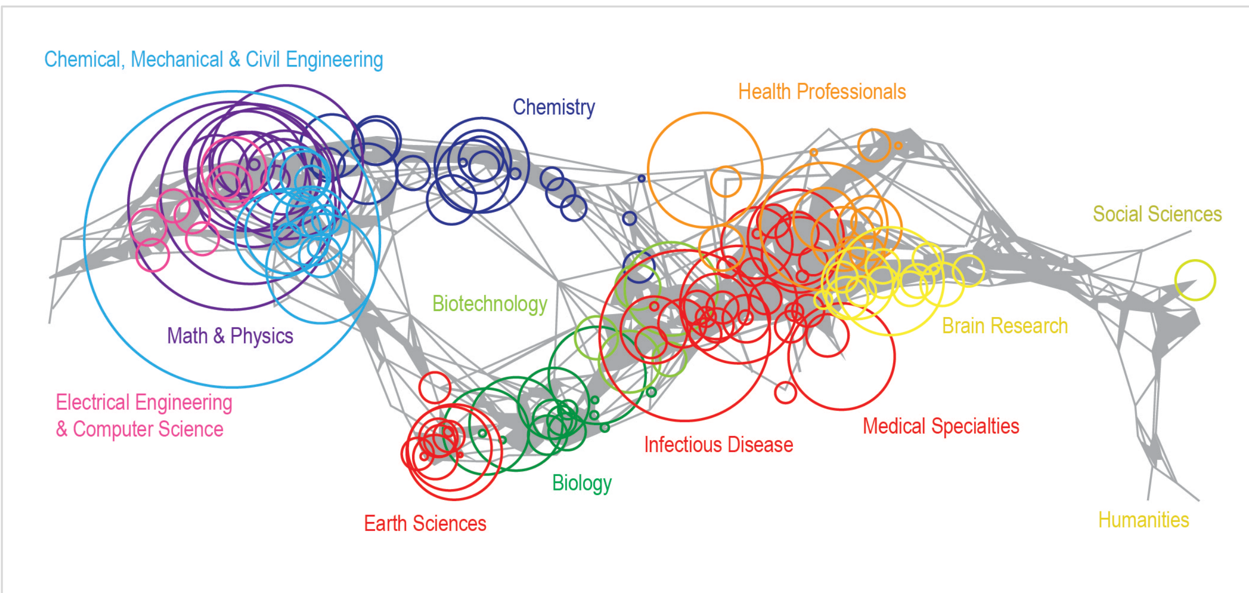

Fig. 7. ISS Map of Science

journals, illustrating the impact that space station research has had in advancing the scientific literature beyond international borders.

3.1.2 Space Station Science is Valuable across Multiple Research Areas

Yet another metric used to determine the scientific value of ISS research is to identify those papers most highly cited in the literature. The following are the top five as of May 30, 2018:

- The *Alpha Magnetic Spectrometer-02* (AMS-02) investigation collected and analyzed billions of cosmic ray events, and identified nine 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. (Times Cited = 489) [18]
- The *Subregional Bone* investigation found that the greatest space-induced bone loss occurs in pelvis, hip, and leg bones, which should guide the focus of countermeasures and evaluation of surface activities designed for space explorers on future missions beyond LEO. (Times Cited = 381) [19]
- The *Microbe* investigation implicated that the Hfq (RNA chaperone) protein acts as a major post-transcriptional regulator of Salmonella gene expression. (Times Cited = 232) [20] The knowledge

gained has been the focus of commercial and academic entities toward the discovery of novel therapeutic and vaccine approaches leading to the implementation of new strategies for translation of this research into health benefits for the general public.

- 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. (Times Cited = 231) [21]
- The *Monitoring All-sky X-ray Imager* (*MAXI)* investigation, 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, and this first-ever observation contributes to a better understanding of the current state and evolution of the universe. (Times Cited = 228) [22]

3.1.3 Space Station Science is Interdisciplinary

The ISS Map of Science [Figure 7] 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 [23].

The UCSD Map of Science is a reference-standard, disciplinary classification system derived from articles and citations contained in more than 25,000 journals tracked and indexed 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 Creative Commons Attribution-Non Commercial- ShareAlike 3.0 Unported (CC BY-NC-SA 3.0) license (https://creativecommons.org/licenses/by-nc-sa/3.0/). [23]

Overlaid on the standard UCSD Map of Science framework, and using its algorithm, the ISS Map of Science 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. [24]

3.2 Highlights of Scientific Results

The diverse array of space station research has led to a steady stream of publications among the international partnership that has 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, space science, 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. For example, results from medaka fish, *C. elegans*, rodent studies, and human research have provided new information about bone metabolism, organ tissue changes, and sensorimotor function that allows researchers to better understand the adaptations that occur to living systems in microgravity. [25-32] After decades of studying bone health in space, investigators found that resistance exercise, coupled with adequate energy intake and vitamin D, can maintain bone mass density in most regions for astronauts on the space station during 4- to 6-month missions in microgravity. This provides evidence that improving nutrition and resistive exercise during spaceflight can mitigate the expected bone mineral density deficits historically seen after long-duration microgravity missions. [33]

The addition of several recent new capabilities on ISS have also facilitated an onboard analysis of microbiological and genetic samples for the first time in spaceflight history. [34-35] Studies enabling 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. [36-37] 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. [38]

Developing technology for cultivation of higher plants will offer the possibility of introducing greenhouses as supplemental sources of fresh food during exploration-class missions. 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. [39-40] Results also showed that at least four successive generations of higher plants could grow and develop in spaceflight conditions.

As astronauts will soon start exploring beyond Earth's protective magnetic field, they will be exposed to more space radiation such as galactic cosmic rays and solar particle events. A combination of passive and active radiation dosimeters on the space station have shown 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 during solar events and alterations in the ISS attitude. [41] Several attempts to study radiation have 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. [42-43] 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 role in ensuring the safety of space exploration. Space station research has suggested that Kevlar fabric has shielding properties similar to that of traditional polyethylene material, but with greater impact resistance and flexibility, making Kevlar a candidate in an integrated shielding approach to future spacecraft designs. [44]

Without the dominating force of gravity on the space station, different physical properties tend to govern systems, and researchers harness these behaviors for a wide variety of investigations in the physical sciences. 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, and strength and wear capacity. [45-46] In recent combustion studies on ISS, combustion below typical temperatures (a.k.a., cool flames) were observed unexpectedly following the radiative extinction of burning fuel droplets, opening up new areas of combustion research in space that can lead to advancements in spray combustion and fire safety. [47] Results from space station fluids investigations have allowed investigators to compile a video database of capillary and fluid flows in microgravity, thus contributing to better computer models when designing fluid transfer systems on future spacecraft. [48]

The space station also provides both vantage point and infrastructure for powerful instruments that study our universe. In addition to the "top-5" paper in *Nature* discussed in 3.1.2, MAXI results have yielded the discovery of five new black-hole candidates and contributes to observation of transient events in space such as binary X-ray pulsars, stellar flares, active galactic nucleus, tidal disruption of a star by a massive black hole, and hypernova remnants. [22, 49-50]

From an average altitude of about 400 km, details of Earth in such features as glaciers, agricultural fields, cities, and coral reefs can be combined with other sources of data, such as those from separate satellites, to compile the most comprehensive information available. Researchers have used ISS remote sensing data to develop an algorithm that relates spectrometer data to CO2 uptake in an ecosystem, and demonstrated that imagery from the space station can be used to map spatial patterns and improve understandings of ecosystem and agricultural productivity. [51] Microwave radiometry results from the space station 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. [52-54]

3.3 In Summary

The small sample of metrics and highlights in this section were selected from the 2,135 ISS research publications and clearly show the outstanding diversity in the science performed. So far, the research has not only addressed several risks of human spaceflight, but also improved our knowledge of the universe and contributed to the development of new technologies or processes that apply to our daily lives. Considering the challenges of performing research in the environment of space, these results are a tribute to the ingenuity and spirit of collaboration of all the contributing countries. Given the number and significance of results achieved in the relatively brief scientific phase of the space station mission (since 2011), more innovations, 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.

4. Benefits for Humanity: Narrative Stories

Economic valuation (EV) and scientific valuation (SV) are a major focus of the third edition. However, the objectives and content of the first and second editions continue via updates to previous stories as well as new stories, organized by the same five benefit areas used in the second edition: economic development of space, innovative technology, human health, earth observation and disaster response, and global education.

4.1 Economic Development of Space

The space station has proven its value as a platform for advancing the boundaries of understanding in a broad portfolio of research disciplines as well as technology development areas. However, it also serves as an incubator for new businesses and testbed for new business models. This allows an opportunity for a shift from a paradigm of government-funded, contractor-provided goods and services to a commercially provided, government-as-a-customer approach.

This interest in promoting a more commercially oriented market 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. Third, it ensures strong industrial capability not only for future spaceflight but also for the many related industries. Finally, and perhaps most importantly, it allows cross-pollination of ideas, processes, and best practices, as a foundation for long-term economic development.

4.1.1 ISS Research Facilities: Public-private Partnerships

The ISS is not a traditional asset where concepts like return on investment (ROI), payback period or risk-adjusted return are easily applied. Instead, its benefits to humanity emerge as catalysts for technological innovations, space utilization, and more recently, commercialization.

Commercial research facilities have greatly increased the breadth of activities and number of businesses actively using the ISS. One example is NanoRacks, LLC, which built and currently operates the first commercial research facility on the outside of the ISS. To date NanoRacks has supported over 300 investigations on the ISS, both internal and external to the station, including:

- NanoRacks-PCG Therapeutic Discovery, which tested whether microgravity improved the crystallization of two proteins that are important for future treatment of heart disease and cancer [55]
- NanoRacks- Hydrofuge Plant Chamber Experiment, which aimed to overcome the behavior of water in microgravity and how it created root rot in a plant system [56]
- Over 200 student-designed payloads, from elementary education through university graduate student level.

Increase in access to space has resulted from changes to NASA policies that streamlined certification of self-contained experiments and led to as much as a three-fold reduction in the cost of conducting research between 2006 and 2018. In 2006, the cost for conducting educational research projects that did not require specialized equipment was typically under $100,000, however researchers also had to consider costs for the development, flight qualification, and integration. [57] NanoRacks currently charges $35,000 for a basic NanoLabs cube-lab module. For this price, NanoRacks coordinates documentation, transportation, installation, and interfacing with NASA to enable 30 days of research on ISS. [58]

There are at least 15 active commercial facilities on ISS, operated by companies like NanoRacks, BioServe, Made In Space, Space Tango, TechShot, and Teledyne Brown Engineering. Many of these have invested their own resources to develop on-orbit research and development facilities, reducing the federal sector risk in offering these facilities and services. These companies locate research customers through the ISS international partners, CASIS, and their own business development efforts.

Expansion of commercial facilities is ongoing, with a number of enterprising companies targeting LEO in general and the ISS in particular as integral elements of their business plans. For instance, Axiom Space has plans to construct an ISS module in 2020 that will eventually detach and become an independent platform. [59] Bigelow Aerospace is also targeting 2020 for the docking of its XBASE expandable space station. [60]

4.2 Innovative Technology

The ISS research portfolio includes many engineering and technology investigations designed to take advantage of the unique microgravity environment. Experiments investigating thermal processes, nanostructures, fluids and other physical characteristics are taking place to provide innovations in those fields. Additionally, advanced engineering activities operating in the space station infrastructure are proving next-generation space systems to increase capabilities and decrease risks to future missions. Emerging materials, technology, and engineering research activities are developing into benefits for economic development as well as quality of life for people on Earth. Descriptions of a few of these research areas follow.

4.2.1 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 ISS water quality have led to advancements in water monitoring here on Earth. [61] Investigations into the basic dynamics of how fluids move in space have also led to advances in medical diagnostic devices. [62]

4.2.2 Materials

In microgravity, the absence of sedimentation and buoyancy-driven convection enables researchers to witness how materials change and develop over longer periods. This allows them to manipulate 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.

Materials science research is addressing the world's ecological and economic challenges, with the main goal of this research being to increase understanding of material solidification processes. This will allow us to develop new, stronger lightweight materials that will not only be of benefit to commercial interests, but will also help with global issues like fuel efficiency and the consumption and recycling of materials. [63]

4.2.3 Robotics

Having robots work alongside humans has the potential to improve the safety and efficiency of human space flight operations, by eliminating tasks that are monotonous or risky or those that impose on the time astronauts need to conduct science experiments. The ISS provides an environment where these operational concepts and procedures can be developed, tested and evolved while demonstrating robotic systems performance and reliability over the long duration. The resultant technology, with its requisite precision and reliability requirements, have led to advanced robotic capabilities for use on Earth, e.g., automation in manufacturing processes that improves safety for human technicians and increases industrial efficiency. [64]

4.3 Human Health

ISS enables investigations that improve human health in space and may inform innovations for health on Earth. Unique perspectives come from comparing spaceflight effects on physiology to disease processes on Earth. Driven by the need to support astronaut health, several biological and human physiological investigations have yielded important results that we on Earth can also benefit from, including advances in knowledge on cardio-vascular physiology, new ways to mitigate bone loss, insights into bacterial behavior, and innovative wound- healing techniques. Advances in telemedicine, disease models, psychological stress response systems, and nutrition and cell behavior are just a few more examples of the benefits that have been gained. [65-71]

4.3.1 Health Technology

ISS robotic technology has been brought back to Earth and integrated with advanced imaging, making difficult surgeries easier and previously impossible surgeries possible. Soon, this technology will enter clinical trials for use in the early diagnosis and treatment of breast cancer by providing improved 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. For laser surgeries used to correct eyesight, a new technology developed on ISS is now used on Earth to track the patient's eye and precisely direct a laser scalpel. Thermal regulation research on ISS has led to sensor technology to better monitor a patient during surgery. [72-75]

A lightweight, easy-to-use device to measure nitric oxide in air exhaled by ISS astronauts is used to detect study possible airway inflammation before health problems occur. This device is now used on Earth to monitor asthma patients, leading to more accurate medication dosing, reduced attacks, and improved quality of life. [76]

Cold plasmas (charged gases that can permeate many materials and spread evenly and quickly) researched on ISS can be used to disinfect chronic wounds, neutralize bacteria, boost tumor inactivation, and even jumpstart plant growth. [72]

4.3.2 Preventing Bone Loss

Without intervention, astronauts would lose significant bone mass density when in space. Countermeasures developed through ISS research have delivered a significant reduction in bone loss and renal stone risk through such interventions as exercise, dietary changes, and pharmacological interventions. In addition, improved scanning technologies enable both early detection of osteoporosis and the development of more effective countermeasures, which will improve our ability to manage osteoporosis in humans on Earth. [77]

4.3.3 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 stress (for astronauts, spaceflight provides that stressor). 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, which can lead to earlier treatment and prevent the onset of painful shingles. [78] Microgravity studies on ISS help researchers pinpoint genetic triggers for immune responses in T-cells informing possible treatments on Earth for immunosuppression. Determining the changes that occur to the immune system due to spaceflight is relevant for developing targeted countermeasures to adverse effects in astronauts, and provides additional information for understanding the complex immune system in ways that could be applicable to autoimmune diseases or organ transplants. [79-80]

4.3.4 Developing New Therapies

Studying the unique and complicated structures of proteins linked to disease in the human body is an important pathway for development of medical treatments. Microgravity allows unique conditions for growth of protein crystals because there are no gravitational effects to disrupt their growth. [81] 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 revealing a new inhibitor several hundred times stronger than a prototype inhibitor. [82]

Microencapsulation is the process by which tiny, liquid-filled, biodegradable micro-balloons are created containing 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 other devices that will aid in the drug delivery using this technology. Progress continues towards future clinical studies in cancer patients. [83]

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. [84]

4.3.5 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, archea, fungi and algae have a detrimental or a beneficial impact on our daily lives. This research has far-reaching effects, feeding into many different areas of biotechnology, as microorganisms have a role in microbiome and health as well as 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 in supermarkets, high-end refrigerator technology, and in trucks that carry groceries to remote regions of countries such as India, Saudi Arabia and Kuwait. Units have also been used in clinics, operating rooms, neonatal wards and waiting rooms, making these locations safer for their inhabitants. [85]

Study in space of plant root zone substrates allowed scientists to improve predictions of how artificial soils will behave when irrigated both in space and on Earth in experimental forests. [86]

4.3.6 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. [87]These technologies have been applied to examine motor vehicle drivers and civil aviation pilots to evaluate risks and prevent accidents. Twenty-four-hour electrocardiograms (ECGs) of astronauts were also analyzed to understand the space environment's effect on biological rhythm and cardiac autonomic nervous activity leading to recommendations for maintaining a well-balanced biological rhythm on Earth. [88]

4.3.7 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 has been tested to train patients and astronauts to acquire the ability to suppress vertigo, dizziness and equilibrium disturbances. [89]

4.4 Earth Observation and Disaster Response

ISS is a global observation platform that can help in understanding 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 internal Window Observational Research Facility (WORF). The 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. The astronauts may also provide input to ground personnel programming the space station's automated Earth observation systems. 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.

4.4.1 Environmental Earth Observations

ISS offers a unique vantage for observing the Earth's ecosystems and atmosphere with both 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. This flexibility is an advantage when unexpected natural events such as volcanic eruptions and wildfires occur.

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 and at about twice the altitude of the ISS. 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.

One feature of oceanographic research 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. [90]

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. 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. [91]

4.4.2 Disaster Response

The advantage of having a human crew to respond to current conditions 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). 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. [92]

Another international collaboration framework is 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 – which are very beneficial for disaster support - both from internal handheld cameras and from externally mounted cameras. [93]

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. ISS capabilities provide a useful complement to autonomous sensor systems in higher-altitude polar orbits.

4.4.3 Tracking Global Marine Traffic and Saving Lives

The Vessel Identification System on the space station has successfully monitored maritime traffic since 2010. This has not only shown great improvements in monitoring global maritime traffic, it has saved lives. Automated Identification System (AIS) signals have been tracked and lives saved due to implementation of this technology on ISS. The Vessel Identification System can also benefit law enforcement, fishery control campaigns, maritime border control, and maritime safety and security issues including marine pollution survey, search and rescue, and anti-piracy. [94]

4.5 Global Education

Spaceflight has a unique ability to capture the imaginations of both students and teachers worldwide.

The presence of humans on 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 (ARISS), Asian Try Zero-G, and Synchronized Position Hold, Engage, Reorient Experimental Satellites (SPHERES) 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. [95-97]

4.5.1 Inquiry-Based Learning

Since the first ISS modules were launched, 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.

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. 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. [98]

ISS genetic research includes the annual Genes in Space™ (https://www.genesinspace.org/) competition, where students (grades 7-12) design experiments to send to the space station. Five finalists present to a panel of judges at the annual ISS Research and Development (R&D) Conference, and the winning experiment is launched the following year. The program is supported by a partnership between Boeing, CASIS, miniPCR, Math for America, and New England Biolabs. [99]

4.5.2 Inspiration

The presence of astronauts aboard the ISS serves as an inspiration to students and their teachers worldwide. Connecting with crew members—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). [100]

Another inspirational connection, 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 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. [101]

5. Conclusions

The ISS, enables discoveries and technology developments by virtue of the unique environment in which it exists. Establishment and maintenance of the spacecraft is a monumental achievement unto itself. Even so, its list of achievements continues to expand through its contributions to science, technology, and the economic development of space.

Although low-earth orbit is barely beyond the edge of the safe cocoon in which we live, it contains almost all the elements needed to obtain answers to questions that will allow us to take the next steps beyond earth’s gravitational field. In the process of answering those questions, we will develop a new space economy while also bringing home benefits that will serve our global community.

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