

Benefits of International Collaboration on the International Space Station

International Space Station Program Science Forum

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Abstract

The International Space Station is a valuable platform for research in space, but the benefits are limited if research is only conducted by individual countries. Through the efforts of the ISS Program Science Forum, international science working groups, and interagency cooperation, international collaboration on the ISS has expanded as ISS utilization has matured.

Members of science teams benefit from working with counterparts in other countries. Scientists and institutions bring years of experience and specialized expertise to collaborative investigations, leading to new perspectives and approaches to scientific challenges. Combining new ideas and historical results brings synergy and improved peer-reviewed scientific methods and results.

World-class research facilities can be expensive and logistically complicated, jeopardizing their full utilization. Experiments that would be prohibitively expensive for a single country can be achieved through contributions of resources from two or more countries, such as crew time, up- and downmass, and experiment hardware. Cooperation also avoids duplication of experiments and hardware among agencies. Biomedical experiments can be completed earlier if astronauts or cosmonauts from multiple agencies participate. Countries responding to natural disasters benefit from ISS imagery assets, even if the country has no space agency of its own. Students around the world participate in ISS educational opportunities, and work with students in other countries, through open curriculum packages and through international competitions.

Even experiments conducted by a single country can benefit scientists around the world, through specimen sharing programs and publicly accessible “open data” repositories. For ISS data, these repositories include GeneLab and the Physical Science Informatics System. Scientists can conduct new research using ISS data without having to launch and execute their own experiments. Multilateral collections of research results publications, maintained by the ISS

international partnership and accessible via nasa.gov, make ISS results available worldwide, and encourage new users, ideas and research.

The paper explores international collaboration history, its evolution and maturation, change of focus during its different phases, and growth of its effectiveness (in accordance with the especially established criteria) in the light of benefits for the entire ISS community.

With the International Space Station extended through at least 2024, more crew time becoming available and new facilities arriving on board the ISS, these benefits of international scientific collaboration on the ISS can only increase.

1. Introduction

Major scientific endeavors are very often the result of international collaboration, bringing together a variety of resources, points of view and expertise. The International Space Station (ISS) is a perfect example of this strategy to create synergy between scientific teams and enhance benefits of the research conducted in this unique space laboratory. The ISS partners are actively ensuring that the best science possible is performed in Low Earth Orbit through the efforts of the ISS Program Science Forum (PSF), International Space Life Science working Group (ISLSWG), and other interagency cooperation. This constant effort explains why international collaboration on the ISS has expanded as ISS utilization has matured.

International scientific collaboration on the ISS takes place in many ways. Collaboration is initiated between scientists. It can result from coordination among sponsors through international working groups. And it can result from the space agencies coordinating access to International Partners' ISS and ground resources for their scientists.

This paper will explore types of international research collaboration that have been conducted on the ISS, and some of the different methods in which the collaborations are initiated and implemented.

2. Counting and Reporting ISS Utilization Statistics

Since, by intergovernmental agreement [1], the purpose of the ISS is to “enhance the scientific, technological and commercial use of outer space”, the ISS Partnership places great importance on measuring, tracking and reporting international research cooperation in space.

The ISS Program Science Forum (PSF) is a multilateral forum composed of representatives of all ISS partners and one of its responsibilities is to enhance, track and publicize the scientific, technological, and educational accomplishments of the ISS. The ISS PSF also tracks whether the research is considered to represent “international collaboration”. The research is tracked according to a PSF protocol (agreement) called “Program Science Forum Guidelines for the Counting of Investigations”, also known as the PSF “Investigation Counting Protocol”.

The basic unit for measuring ISS research is called an Investigation. The PSF considers an investigation to have the following characteristics: (1) a research objective (usually with a one or more related hypotheses), and (2) an investigator or research team working to achieve the objective, (3) activities completed on ISS to achieve these objectives, and (4) scientific publications that are to be produced by the investigators when the research is complete. (The term “experiment” is sometimes used to describe discrete research activity; “experiment”, however, has different definitions and implications among the different Partner agencies, so ISS PSF uses “investigation” and its definition in counting and reporting. Nevertheless, the term “experiment” may also be used in this paper.)

The ISS international partners have reported the following statistics through ISS Expedition 48, through September 2016 (the latest statistics approved by the ISS Multilateral Coordination Board): 2179 investigations, 3145 principal and co-investigators (scientists leading an investigation), and 98 countries participating through research and/or education and outreach. Figure 1 shows the numbers of investigations assigned to individual agencies, and categories of scientific research/utilization. Figure 2 shows the general trend of Investigations and Investigators since the beginning of the ISS operations. This data is updated regularly by each of the PSF members, published on NASA web site after approval by ISS Program Managers and used by all ISS partners to monitor the trends in ISS utilization and results.

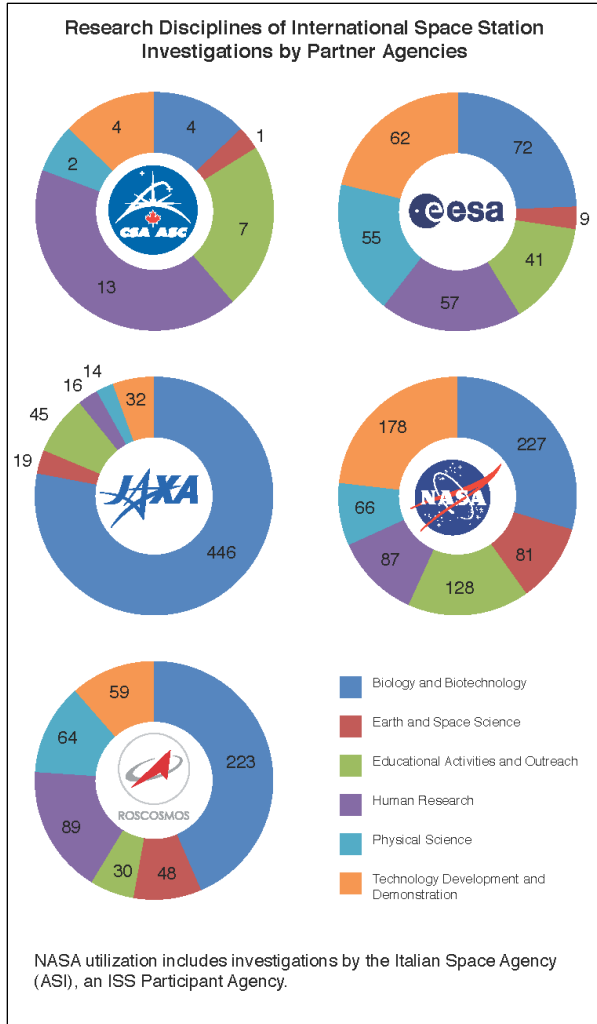


Fig. 1: Research Disciplines of International Space Station Investigations by Partner Agencies in Expeditions 0-48.

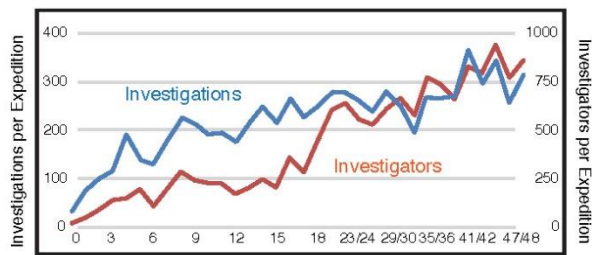


Fig. 2: Number of Investigators with Research on ISS and Investigations per Expedition – Expeditions 0-48

3. ISS Research and International Collaboration

International collaboration in space is beneficial in many respects. Broadening scientific participation brings new perspectives to the design of experiments and analysis of results. World-class research facilities can be

expensive and logistically complicated, jeopardizing their full utilization; experiments that would be prohibitively expensive for a single country can be achieved through contributions of resources from two or more countries, such as crew time, up- and downmass, and experiment hardware. Cooperation also avoids duplication of experiments and hardware among agencies. Collaboration by scientists from two or more countries acts to expand the access to ISS research for the countries' respective space agencies. As an example, an investigation called Test of Reaction and Adaptation Capabilities (TRAC) submitted by a German investigator was associated with a Canadian experiment, Perceptual Motor Deficits in Space (PMDIS), and both were performed on the ISS in 2006[2]. In addition, multinational publications may have greater scientific impact[3].

Through the ISS PSF, each agency reports the number of investigations it has “led” or “sponsored”. The agencies also report scientists who are principal investigators and co-investigators for each investigation. Investigations are counted as having international collaboration if they are sponsored by one of the ISS Partner agencies and include scientists from one or more other countries.

Table 1 shows how international participation and collaboration increases the impact of ISS utilization. The column “Agency Only” shows the number of investigations reported by the agency that did not have scientists from outside that agency. The column “Collaboration (Hosting)” shows the number of investigations “hosted” by that agency, with scientists from countries outside of that agency. Here the term “hosted” is used instead of “led” or “sponsored”. The column “Investigations Implemented” is the sum of the previous two columns, which is also the number of investigations reported by each agency as shown in Figure 1. The column “Collaboration (Participating)” shows the number of investigations which were reported by other agencies as having scientists from that agency’s country (or in ESA’s case, one of ESA’s member countries). The column, “Total Agency Impact”, shows the sum of “Investigations Implemented” plus “Collaboration (Participating)”. The final column, “% Increase Through Collaboration”, shows the percentage of collaborative investigations as compared to Investigations Implemented for each agency.

Agency	Agency Only	Collaboration (Hosting)	Investigations Implemented	Collaboration (Participating)	Total Agency Impact	% Increase Through Collaboration
CSA	22	9	31	25	56	45%
ESA	222	74	296	273	569	48%
JAXA	405	167	572	102	674	15%
NASA*	593	174	767	93	860	11%
Roscosmos	316	197	513	192	705	27%
			2179	685	2864	24%

Table 1 International Collaboration Expands ISS Partner Agencies' Utilization Impact

The “Total Agency Impact” and “% Increase Through Collaboration” columns show the benefit of increasing ISS utilization through international cooperation. Agencies increase the access to ISS for other countries’ scientists. Graphical representation of these increases in comparison with “Agency Only” investigations is presented in Figure 3. In the case of CSA and ESA, the effective participation in ISS research almost doubles.

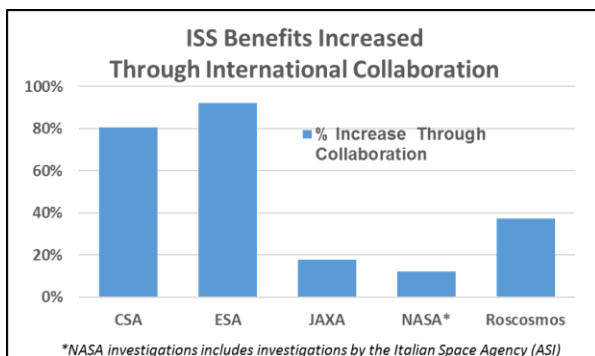


Figure 3 ISS Benefits Increased Through International Collaboration

Summing the “Collaboration (Hosting)” column of Table 1 yields a count of over 600 investigations, or more than a quarter of the overall investigations implemented. A review of the individual experiment names (using data internal to the PSF statistics specialists) would show slightly over 400 unique investigation or experiment names. By agreement within the PSF Investigation Counting Protocol, very similar investigations are grouped one overall investigation name. A predominant example is the protein crystal growth (PCG) category, where many different proteins, serving different scientists, are flown in one group and use the same experiment hardware and facility. Other examples include educational projects that serve many schools and hypotheses within the same

campaign, and biological tissue sharing programs that serve multiple scientists from one batch of experimental subjects, such as rodent research.

The PSF has encountered one difficulty in its reporting of international collaboration statistics. When scientists from more than one country are involved in an investigation, or resources are provided by more than one space agency, it can be difficult to assign an investigation to “count” toward one agency versus another. Therefore, international participation and contributions are tracked and reported as investigations that are “hosted” by an agency, and investigations in which the agency’s country’s scientists “participated”. The PSF acknowledges that two or more agencies may combine resources and both consider that they are “leading” or “sponsoring” the same set of operations, sometimes meeting the needs of two different scientists who may choose to publish separately or together. In these cases, we may count each version of the experiment separately. While this situation is not desirable, it is an excellent indicator of the flexibility of the ISS partnership agreements in optimizing international contributions to do science across many different facilities and capabilities.

The PSF uses a Venn diagram to report the distribution of international collaboration (Figure 3). The Venn diagram shows the possible inter-agency combinations for participation, and the number of investigations in each category. (Note that Italian Space Agency (ASI) investigations are represented in two areas – as one of the member countries of the European Space Agency, and through bilateral agreements with NASA.)

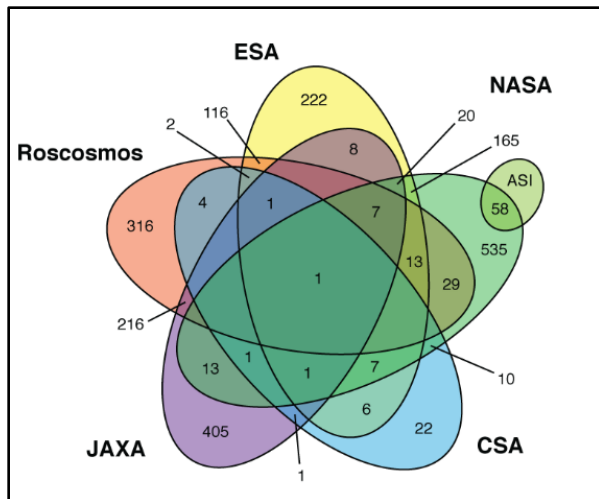


Figure 4: Venn diagram showing combinations of ISS agencies' international collaboration during Expeditions 0-48.

Studying collaborations by research category yields the largest number of collaborations at 351 in Biology and Biotechnology. The bulk of these collaborations are 208 protein crystal growth investigations with JAXA and Roscosmos. Physical Science has second highest number of collaborations at 96 plus it has the most collaboration combinations. Human Research also has a high fraction with 88 collaborations, predominantly by NASA with other partners. Figure 5 shows the distribution of collaborations by research category.

International Collaboration
Percentage by Investigation Categories

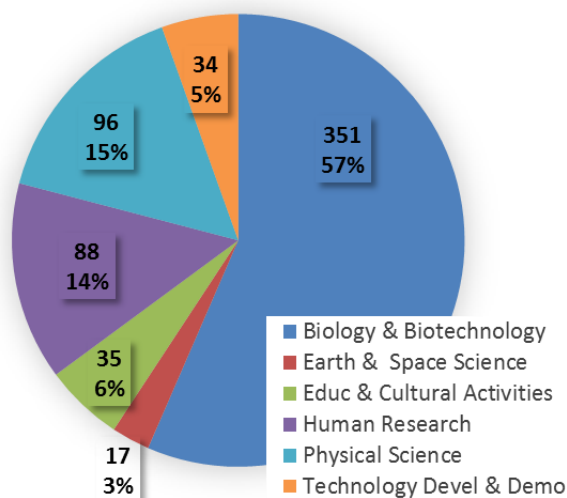


Figure 5: Graph showing international collaboration by research category

It may be interesting to review the investigations that have the “most” international participation in terms of ISS partner agencies. (Details of these investigations,

and of all ISS investigations as reported by the ISS Partner agencies, are found at www.nasa.gov/iss-science unless otherwise annotated.)

Partnership-wide Collaborations - One investigation officially has had participation by scientists reflecting all five agencies. The Fundamental and Applied Studies of Emulsion Stability (FASES) operated in ESA’s Columbus module in the Fluid Science Laboratory rack, during 2013 and 2014. FASES studied emulsions, a mixture which results when one liquid is added to another and is mixed with it but does not dissolve into it. The foreseen scientific benefits included improved knowledge of how to stabilize or destabilize emulsion products, and improved modeling of emulsion dynamics for use in commercial and industrial applications.[4]

Four-partner Collaborations - Seven investigations have represented ESA, JAXA, NASA and Roscosmos:

- Dose Distribution Inside ISS - Dosimetry for Biological Experiments in Space (DOSIS-DOBIES): Measured nature and distribution of the radiation field inside the ISS and developed a standard method to measure the absorbed doses in biological samples onboard the ISS
- Dose Distribution Inside the International Space Station - 3D (DOSIS-3D): Uses several active and passive detectors to determine the radiation doses inside the ISS. The goal is a three-dimensional radiation map covering all sections of the ISS.;
- ESA Education Payload Operations - Foam Stability 2 (ESA-EPO-Foam S2): Studied aqueous and non-aqueous foams in the microgravity, particularly the so called “wet” foams, which cannot be stabilized on Earth[5];
- European Technology Exposure Facility – Dosimetric Telescope (EuTEF-DOSTEL) ISS external instrument measured time-dependent fluence rates of charged particles and their corresponding dose rates and linear energy transfer (LET) spectra. [6]
- Matroshka-2 Kibo and Matroshka-2B used a phantom human torso to measure the distribution and dose of particle radiation in the human body, both outside and inside ISS. [7], [8];
- Plasma-Krystal-3 Plus (PK3+): studied the properties of complex (dusty) plasma formed by electrically charged dust particles which arrange in a regular macroscopic crystal lattice. [9]

One suite of investigations represented ESA, CSA, JAXA and NASA: the International *Caenorhabditis elegans* Experiment First (ICE First) complement of roundworm biology experiments. The sub-experiments investigated Aging, Apoptosis, Cells, Development, Genomics, Muscle Proteins and Radiobiology. [10]

One investigation represented ESA, CSA, JAXA and Roscosmos Selected Optical Diagnostic Instrument

- Diffusion Coefficients in Mixtures (SODI-DCMIX). The experiment studied the thermodiffusion properties of water-based and hydrocarbon mixtures. [11]

4. Early Collaboration

The “Interactions” investigation was one of the first fully international experiments on ISS, with scientists from the United States and from the Institute of Biomedical Problems (IBMP) in Russia, continuing a cooperation that began during the Shuttle-*Mir* program. Interactions used weekly questionnaires to observe relations between crewmembers as well as ground support teams in Houston, Texas, Huntsville, Alabama, and Moscow Russia. The investigation was conducted on ISS from Expedition 2 in 2001 through Expedition 9 in 2004. Differences were seen in mood and group perceptions between Americans and Russians, and between crewmembers and Mission Control personnel. The results of the study have informed subsequent crew and ground team preparation for extended missions, as well as future exploration missions of longer duration and more isolation.[12]

The Protein Crystal Growth - Enhanced Gaseous Nitrogen Dewar (PCG-EGN) flew on Space Shuttle ISS assembly missions prior to the first Expedition crew arrival, continuing the program begun during the Shuttle-*Mir* program. PCG-EGN grew protein crystals to test a low cost, simple experimental platform. Thirty-two different proteins were used during four expeditions, with a French scientist being added to the collaboration during Expedition 4 in 2001-2002.

The National Space Development Agency of Japan (NASDA) and the Russian Space Agency (RSA) (agencies now called JAXA and Roscosmos) conducted in 2001-2005 two very interesting and pioneering experiments. The Micro Particle Capturer & Space Environment Exposure Device (MPAC & SEED) hardware was mounted on the exterior of the Russian Service Module, and samples of exposed materials and captured particles of increasing duration were returned to Earth after Russian space walks.[13] A high definition television (HDTV) experiment system evaluated benefits for medical and psychological support of cosmonauts, and promoted interest in ISS and space among the public.[14],[15] In spite of the fact that these experiments were done under contract between NASDA and RSA aboard the ISS, these investigations can be considered as an excellent example of collaborative efforts of Japan and Russia at early stage of the ISS utilization (with involvement of scientists and engineers from both sides, and cosmonauts on board as well).

5. Assembly-Driven Collaboration

A core principle of the International Space Station Partnership is that as each agency contributes resources to the assembly, operation and maintenance, each agency

then receives an allocation of the resources available on the ISS. During the early phases of assembly of the ISS, much of the focus was on completing the infrastructure necessary to support the launch and activation of the International Partners’ laboratory modules and facilities. This focus on “systems” meant greatly reduced resources available to scientists, especially crew time and launching hardware and returning samples. Through international cooperation among the space agencies, however, opportunities for “early utilization” were created to allow an scientific returns on the Partners’ investments.

A good example is the so called Early Utilization Agreement settled between NASA and ESA in 1997. ESA provided three science support facilities to NASA in exchange for opportunities for ESA to perform science onboard ISS before the ESA *Columbus* laboratory was launched (in 2008). ESA provided the Microgravity Sciences Glovebox (MSG), the Minus Eighty degree Laboratory Freezer for ISS (MELFI), and the Hexapod. The MSG, launched in 2002, provides a sealed environment for conducting science and technology experiments, including experiments with hazardous aspects that require handling by crewmembers. The first of three MELFI facilities was launched in 2006, on the first Space Shuttle mission following the *Columbia* tragedy. The ability to freeze human and biological samples in conditions similar to ground laboratories is a critical element of the ISS laboratory. The Hexapod pointing system was launched in 2017, and is the pointing platform for the Stratospheric Aerosol Gas Experiment III (SAGE III).

Among the early utilization experiments that ESA was able to implement was the European Modular Cultivation System (EMCS). EMCS facility was integrated within a NASA rack and started science operations in 2006, and continues to be used by US and European scientists.

Another example of inter-agency agreements is the Multipurpose Logistics Module (MPLM) agreement between NASA and ASI. ASI produced several MPLM units which were key elements during Space Shuttle assembly missions for delivery of cargo including scientific racks. (ASI used similar technology to build the Nodes 1,2 and 3 for NASA and the *Columbus* module for ESA.) As part of the MPLM agreement, ASI received a portion of NASA’s ISS resource allocations to use for research, as well as additional ASI astronaut flight opportunities. [16]

6. International Working Groups

International Science coordination groups have significant success in increasing ISS utilization. Some of these groups have long history, even predating the ISS, while others are more recent.

ISLSWG, ILSRA: The International Space Life Sciences Working Group (ISLSWG) was organized in 1991, well before the ISS first element's launch. The ISLSWG coordinates strategic planning and implementation for space life sciences. Its members represent the space agencies from the US, Canada, the European Space Agency, Japan, France, Germany, Italy and the Ukraine.

While a large focus of the ISLSWG is on the ISS, it also coordinates research opportunities on parabolic flights, sounding rockets, Space Shuttle (retired), and ground facilities. Ground facilities such as bedrest studies and isolation facilities complement ISS research by expanding the understanding of the biological and biomedical phenomena observed in space, or offering analog environments that offload ISS resources.

The ISLSWG has organized seven International Life Sciences Research Announcements (ILSRA)[17],[18]: 1996, 1998, 1999, 2001, 2004, 2009 and 2014 with ISS experiments selected in 2001 through 2014. The ILSRA identifies research focus areas of interest to the member agencies and scientific communities, coordinates research facilities that will be made available internationally, and ensures that funding will be available from the participating agencies. In each ILSRA the participating space agencies agree on a consolidated peer review process. Each agency uses the results of the peer review to decide whether they will fund the work of their scientists in each proposal, and this facilitates investigators from many nations proposing together. The majority of European life sciences investigations flown to ISS to date have been identified through the ILSRA process.

Because many biology research facilities and equipment for measuring physiological parameters in the crew can be used by numerous investigators, the ISLSWG has helped member agencies to share facilities and optimize many other aspects of implementation.

IMSPG: The International Microgravity Science Planning Group (IMSPG) carries out a similar international function for the physical sciences. However, due to the nature of physical sciences investigations, many more investigations require custom hardware. The IMSPG has served primarily as a forum for agencies to let each other know about what experiments are planned and what hardware will be developed to support them. Agencies have then used that knowledge to identify cases where another partner's hardware can be used to save development costs. Many of the IMSPG collaborations then, may not include multinational investigations, but instead a series of national investigations done in shared or exchanged facilities. [19]

The IMSPG has released one International Announcement of Opportunity, during the early phase of

ISS operation, which drew submittals from several international agencies including ASI.[20]

ESA Topical Teams: ESA has used scientific Topical Teams to steer ESA's scientific research strategies and focus. Each Topical Teams includes scientists from various backgrounds and viewpoints, brought together to develop research programs and recommendations. The topical teams also identify industries interested in teaming with scientists to conduct the research through a dedicated ESA Microgravity Application Program (MAP). The teams have demonstrated high success in quality of proposed scientific projects, involvement of industry, international synergy, and potential for impact from the results of the research. [21] ESA topical teams are open to worldwide scientists participation. In particular in material and fluid science the wide participation of international scientists has allowed teams to define and support very resource-intense investigations, using, for example, the Materials Science Laboratory (MSL) and the ElectroMagnetic Levitator (EML).

JWG: The US/Russian Joint Working Group (JWG) on Space Biomedical and Biological sciences was organized and first met in 1971, during the timeframe of the Apollo-Soyuz Test Project, and was then called the US/USSR Joint Working Group on Space Biology and Medicine.[22] The JWG has conducted joint science activities through the subsequent decades, persevering through several difficult political periods between the countries.

The JWG has coordinated joint experiments on Soviet and Russian Cosmos, Foton and Bion satellites, on the US Space Shuttle, and during Shuttle/*Mir* missions. These experiments have used various organisms, including microbes, insects, amphibians, rats and plants. During the Shuttle/*Mir* program and on ISS, the JWG's focus has expanded to encompass innovations in space medicine and biomedical research.

MHRPE: A relatively recent addition to international coordination and collaboration is the Multilateral Human Research Panel for Exploration (MHRPE). The MHRPE was organized in 2011, and chartered by the ISS Multilateral Coordination Board (MCB) to improve coordination of medical operations and biomedical (human) research, and to investigate using the ISS as an analogue and testbed for future exploration. The MHRPE has responsibility for reviewing foreseen health risks associated with long-duration human space exploration, and coordinating plans among the Partners for future human research on ISS to understand and mitigate those risks.

NASA's Human Research Program (HRP) and the Institute of Biomedical Problems (IBMP) of the Russian Academy of Science, acting for MHRPE, developed a joint US-Russian biomedical program for the 2015 One-Year ISS mission of American and Russian

crewmembers. The MHRPE then coordinated an overlapping list of 16 US, 9 Russian, 3 Japanese, 3 European and 1 Canadian investigations were selected to address risk-reduction goals in 7 biomedical categories.[23] The One Year Mission required extensive coordination and leadership from NASA, Roscosmos and the rest of the ISS partnership. It is unlikely that any single country could have overcome the political and logistical challenges (including Soyuz transportation) to conduct a year-long mission within a single national effort.

The MHRPE has also established a Data Sharing Principles document which defines how biomedical research scientists from Partner countries may request ISS crewmember consent and data from past and future investigations.[24]

IMWG: The International Microbial Working Group (IMWG) is another example of international collaboration. It aims to maximize ISS scientific outcomes by implementing strategies to improve on-orbit operational efficiencies such as crew time and consumables, while meeting the requirements both of the research and operations communities simultaneously. For example, the IMWG is developing policies and processes to promote the scheduling of crew microbial sampling on orbit to meet both medical requirements and research requirements in the same sampling session, and with shared hardware. Working groups like these can also improve access for researchers to existing archived materials, such as microbial isolates or environmental samples obtained from all of the international partner modules. Researchers can search the archives first for availability before requesting crew time to obtain on-orbit samples. All of the international partners benefit from these policies, as crew time for additional activities increases, use of each agency's hardware is maximized, and the working group promotes access to the unique and limited national resources maintained in archives for scientists around the world to use in their own ground-based research.

7. International Outreach

ISS utilization includes activities that go beyond traditional hypothesis-drive research to provide worldwide benefits.

International Disaster Charter: ISS assets contribute support to the United Nations' International Charter [on] Space and Major Disasters (<https://disasterscharter.org>). The International Charter aims at providing a unified system of space data acquisition and delivery to those affected by natural or man-made disasters. JAXA contributes data through two high-definition television cameras installed in the Multi-mission Consolidated Equipment (MCE) facility attached to the "KIBO" Japanese Experiment Module (JEM) Exposed Facility (EF). NASA contributes ISS

crew earth observation imagery through the US Geological Survey agency. Any nation affected by a disaster may request assistance from the International Charter, and the participating space agencies make best efforts to provide appropriate data. One of the most recent activations of the charter was in response to Hurricane Harvey, which impacted Texas and Louisiana in the US in August, 2017.

Global Education: The ISS, its astronauts and its environment above the Earth lure the attention of educators and students around the world. International education programs engage students in Science, Technology, Engineering and Math (STEM) subjects, and introduce them to other students and cultures around the world. [25] Students from 88 countries around the world have requested pictures of the Earth through the Sally Ride Earth Knowledge Acquired by Middle school students (EarthKAM) program, through Expedition 48 (September 2016). Students from schools in 50 countries have asked astronauts about living and working in space through the Amateur Radio aboard ISS (ARISS) program. The Synchronized Position Hold, Engage, Reorient, Experimental Satellites – Zero Robotics competition continues to expand, and now has taught high school and middle school students from 22 countries how to “code” or generate computer programs to control robots.

8. High Impact Collaborative Publications

One of the most important legacies of the ISS will be the sharing of results of the research that has been conducted, to ensure the widest benefit of the knowledge gained. International collaboration in analyzing and reporting results may strengthen the analysis, and expand the reach and citation of the results.

The NASA ISS Program Science Office (PSO), in conjunction with the International Partner members of the ISS Program Science Forum, tracks and reports results publications arising directly from ISS research. NASA summarizes significant results and maintains a database of the citations, with links if available, on its website (www.nasa.gov/stationresults). [26] The PSO also tracks publications in high visibility and high impact scientific peer-reviewed journals, as well as numbers of citations.

JAXA's Monitor of All-sky X-ray Image (MAXI) instrument installed on the JEM-Exposed Facility, and the Burst Alert Telescope aboard NASA's Swift satellite, independently observed the moment that a star was sucked into a giant black hole in the center of a galaxy located 3,900,000,000 light years away from Earth. Although the discoveries (first real-time observation of the phenomenon) were made independently and each team could have published their results independently, the teams chose to collaborate and compare data and co-publish the findings. The result was a stronger analysis

of the phenomenon and implications to related astrophysical theories. The paper was published in the highly regarded journal *Nature* in 2011. [27] The MAXI and Swift science teams collaborated again in 2015, reporting on joint observations of rapid X-ray oscillations in a black hole and companion star binary system, which again led to revision of theories associated with the accretion of mass by black holes. Their results were published in *Nature* in 2016. [28]

The Alphaspectrometer-02 (AMS-02) experiment on ISS is managed by perhaps the most international group of researchers to use the ISS, called the “AMS Collaboration” (www.ams02.org). The AMS Collaboration authors have published seven papers in the high-impact journal *Physical Review Letters*. According to ISS Program Science Office internal statistics gathered using Clarivate Analytics® (<http://clarivate.com>), the AMS-02 publications have received the most citations of any ISS investigation, and the MAXI publications have received the next most.

9. Open Data

ISS “utilization” is expanding through scientific data repositories that collect ISS research data and make it available to the public. Government policies are starting to require that data collected with government funding be made available in repositories in the U.S. [29]. In Europe and at ESA, similar regulations are expected in a short time. In addition many journals require published data to be placed in an open archive, and space agencies are recognizing the value of grouping space data with appropriate metadata to enable design of future experiments. Conducting research on ISS presents many challenges, due to the remoteness of the laboratory, logistics and funding issues, competition for resources, etc. Space experiments often generate more data than the principal investigators and science teams use in their analysis and publications. Scientists from many countries are invited to contribute ISS experimental data – raw, processed and metadata – to “open science” databases, such as GeneLab and Physical Sciences Informatics.

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NASA seeks to maximize the impact of biological research, and has established the GeneLab platform (genelab.nasa.gov) to make experiment data publicly available for further research. The GeneLab data repository “will expand scientists’ access to experiments that explore the molecular response of terrestrial biology to spaceflight environments. The vast amounts of raw data generated by experiments aboard the International Space Station will be made available to a worldwide community of scientists and computational researchers.” [30] GeneLab provides access to “omic” data from ISS experiments, including genomics, transcriptomics, proteomics, to new ground researchers who would otherwise not have access to ISS and space experiments. The GeneLab database currently has datasets from Japanese experiments including Medaka Osteoclast, ICE-First and RNA Interference and Protein Phosphorylation in Space Environment Using the Nematode *Caenorhabditis elegans* (CERISE) and Italian rodent research using the Mouse Drawer System (MDS).

NASA has also established the Physical Sciences Informatics program (psi.nasa.gov) to make ISS experimental data available for public use and additional and new research. NASA has begun populating the database with experiment data in the fields of combustion, complex fluids, fluid physics, fundamental physics and materials science.

10. Conclusion

International collaboration and utilization of the ISS has expanded access to the ISS laboratory and its unique facilities. It has also increased the scientific value of the ISS by strengthening the scientific disciplines involved in ISS research. While the governments and agencies of the ISS Partnership have committed to extend ISS through 2024, further extension is not guaranteed. By further increasing the breadth and depth of international collaboration, the International Partners will continue to expand the legacy of ISS scientific discovery and benefits to people on Earth.

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