

Understanding Socio-Technical Issues Affecting the Current Microgravity Research Marketplace

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Abstract— For decades, the International Space Station (ISS) has operated as a bastion of international cooperation and a unique testbed for microgravity research. Beyond enabling insights into human physiology in space, the ISS has served as a microgravity platform for numerous science experiments. In recent years, private industry has also been affiliating with NASA and international partners to offer transportation, logistics management, and payload demands. The Center for the Advancement of Science in Space (CASIS), which manages the ISS U.S. National Laboratory, has developed a diverse portfolio of private, public, international, and outreach projects. As the costs of flying projects to the ISS decrease, the barriers limiting non-traditional partners from accessing the ISS as a platform also decrease. However, the ISS in its current form cannot be sustained forever. As NASA looks towards commercialization of the low Earth orbit (LEO) space and the development of a cislunar station, concrete plans for shifting the public-private relationship of the ISS are unclear. With the consistent need to continue microgravity research – from governments and private industry – understanding the socio-technical and policy issues that affect the marketplace for future microgravity platforms is essential to maintaining an accessible and sustainable space economy. How will the U.S. and other governments design public-private partnerships to pursue economic and social goals in the LEO microgravity ecosystem? What governance structures will influence who is eligible to operate platforms for activities including tourism, research, manufacturing and outreach? How will international collaboration occur in the future LEO microgravity ecosystem? This paper presents a review of the current microgravity research ecosystem with a focus on potential future marketplace dynamics.

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1. INTRODUCTION

For anyone who is a teenager in October 2019, the International Space Station has been in operation and hosted humans for the entirety of that person's life. The platform has hosted a diverse spectrum of microgravity, human space exploration, technology demonstration, and education related research. In recent years, however, a variety of socio-technical issues have influenced a changing landscape of ISS research and the microgravity research ecosystem. Predicting what might happen in this evolving market has become a topic of ongoing analysis studies and discussion in the media [1]–[3]. Many of the current discussions regarding the future of the ISS tend to focus on the U.S. and NASA perspective. This paper is the beginning of a series of work that explores what may drive the future of microgravity research in LEO with a global focus emphasizing accessibility for non-traditional space partners and emerging space nations. The literature review outlines some of the major socio-technical milestones that significantly influenced the execution of the ISS project and identifies issues that may drive the continuing microgravity ecosystem. Current and proposed microgravity platforms for civil and commercial purposes in the LEO environment are reviewed based on publicly available online information as of late 2018. While the feasibility of future proposals is not analyzed in this paper, a framework is offered to evaluate how future proposals embed accessibility to microgravity research.

2. SOCIO-TECHNICAL MILESTONES IN ISS DEVELOPMENT

The ISS is the single largest and most expensive human construction project. An international endeavor, the ISS has been continuously occupied by humans since 2000. International partners include the USA, Russia, Canada, Japan, and the European Space Agency (ESA) member countries and as of June 2018, individuals from 18 different countries have visited the station [4]. Although main construction of the ISS ran from 1998 to 2011, the origins of its development can be traced to the founding charter of NASA.

The National Aeronautics and Space Act of 1958, which formally established NASA, stated that one of the objectives of the newly created agency was "Cooperation by the United

States with other nations and groups of nations in work done pursuant to this Act and in the peaceful application of the results, thereof," (Sec 102 (c)(7)) [5]. In the post-Apollo era, such cooperation engagements evolved from "data exchange, working together on scientific projects and providing launch services for the scientific satellites of other countries" to directly involving foreign partners in providing critical human spaceflight hardware [6]. In late 1969, NASA asked Canada, Europe, and Japan to consider options of participating in post-Apollo human spaceflight. Ultimately, Canada agreed to develop and provide the Remote Manipulator System (Canadarm 1) for the space shuttle and Europe agreed to the option of providing a Research and Applications Module (later called SpaceLab) for the shuttle. Setbacks in projected usage of the shuttle and development delays meant that ESA – established in 1975 – never recouped the development costs of SpaceLab and resulted in some tensions between NASA and ESA [6]. Nevertheless, these post-Apollo cooperation agreements proved that Canada and Europe could manage and build human spaceflight-rated hardware projects. Beyond the experience gained in systems engineering, management and technical knowledge, both these regions and the U.S. gained more confidence in their respective spaceflight capabilities. Such hardware successes contributed to Canada and Europe's ability to approach later cooperative discussions on a more equitable footing.

In 1981, President Reagan nominated James Beggs as NASA administrator and Hans Mark as deputy administrator. At their confirmation hearing, Beggs and Mark announced intent for a permanent, human-tended¹ space station as the next major and logical goal in space [6] [7]. Different NASA field centers had conducted studies on possible space station missions and configurations, but an official program had yet to receive approval. In November 1981, a NASA-wide workshop was held on space station planning, in which international participation and cooperation figured significantly in the discussions [6]. A Space Station Task Force, headed by John Hodge, was formally created in May 1982 and possible international partners were encouraged to run their own requirements studies. In August 1982, NASA awarded contracts to U.S. aerospace firms to conduct independent and parallel requirements analysis studies for a space station. The firms received some pushback from the Department of Defense, however, when they began exploring options for cooperating with foreign firms due to arms control and technology transfer issues. Following such pushback, NASA international affairs officials (Kenneth Pederson and Margaret Finarelli) continued to move forward with the task force, but tactfully chose not to emphasize international involvement in external advocacy discussions in order to avoid resistance from other agencies [6]. In 1982, NASA unsuccessfully sought President Reagan's approval to embark on a space station project. Reagan's July 1982 space policy address transferred space policy leadership from the Office

of Science and Technology Policy to the National Security Council (NSC). Fortunately for space station proponents the space policy representative in the NSC, Air Force Colonel Gil Rye, had participated in the NASA space station workshop in 1981 and believed that building a space station was critical for U.S. national security in the Cold War era [6], [8].

From 1982 to 1984, NASA officials again sought presidential endorsement of a space station, through prescribed working groups and direct discussions with the president and his advisors that were facilitated by Rye [6], [8], [9]. Eventually officials were successful in gaining Reagan's approval. In his 1984 State of the Union address, Reagan not only announced the decision to build the space station, but also invited international participants. Discussions by top national security, NASA, and State department officials right before the address facilitated the inclusion of international cooperation in the speech and bypassed the bureaucracy of policy papers, assessments, and inter-agency meetings that would typically accompany such an announcement [6]. By incorporating the international element into Reagan's speech, officials helped insulate the project from future critics as an attack on the project would come to be seen as an attack on American international prestige [9].

Even after gaining a presidential endorsement, the space station project faced an uphill battle of congressional appropriations, competing field center plans, and difficulty in defining the purpose of the project itself. A development budget for the station was approved piecemeal each year in the late 1980s and estimated total costs of the project began to rise over \$10 billion. Winter of 1985 began with NASA leadership changes and sadly ended with the *Challenger* explosion. The subsequent findings of the Rogers Commission and Augustine Commission, along with Hubble difficulties highlighted management issues within NASA and drove a desire to scale back or even cancel the space station program within Congress. In 1991 and 1993, the space station project, now called "Freedom", narrowly won congressional votes for continued funding. Although individual representatives may have opposed the project, lobbying from aerospace firms, interests of constituent states with NASA centers, and a stake in international prestige helped save the project. In the late 1980s, MOUs had been signed with Canada, Europe and Japan for engagement in the project and by the early 1990s, these partner countries had already spent \$1.6 billion between them on Freedom. Canceling the project would not only be viewed as an affront to these international partnerships but also a waste of NASA dollars that had already been spent [9].

In the midst of these troubles for the space station in the U.S., political winds were shifting on the other side of the globe. The year 1991 marked the dissolution of the Soviet Union and the beginning of financial, logistical and technical troubles for the newly formed Russian Space Agency (RSA).

¹ The original language utilizes the term "manned" but the authors have changed it to keep within current spaceflight terminology.

The RSA was dealing with a sudden loss of funding, revolts at their remote launch site in Kazakhstan, old Mir hardware, and conflicts over the construction of Soyuz hardware. In June 1992, NASA chief Dan Goldin and RSA head Yuri Koptev met and discussed possible solutions for each other's problems - NASA needed increased momentum and funding to keep the space station project going and Russia still maintained most of its spaceflight supply capacity [9]. In 1993, station redesign recommendations by the Vest Committee contained proposals to include Russia in the planning and building of the station. In September that year, Vice President Al Gore, Russian Prime Minister Victor Chernomyrdin, and the respective space chiefs signed a deal for Russia to be involved in the space station, renaming the project International Space Station Alpha [10]–[12]. The deal not only helped keep the space station program alive, but was beneficial for foreign policy interests to stabilize relations with Russia as a whole.

In 1995, Boeing signed a \$5.6 billion deal for the prime ISS contract and Johnson Space Center (JSC) was designated as leader of the project. Following NASA successes with fixing the Hubble Space Telescope and public support after the release of the feature film *Apollo 13*, NASA chief Goldin sought and won a multi-year authorization of the space station program [9]. Doing so assured long-term funding for the proposed station construction years and satisfied international pressure to continue the project. Following approval of the multi-year authorization in the U.S., ESA also voted to continue support of the ISS. In January of 1998, the ISS Intergovernmental Agreement (IGA) was signed between the U.S., Canada, member states of ESA, the government of Japan, and the Russian Federation on the cooperation of the civil International Space Station [13].

In November 1998, the *Zarya* module was launched by Russia as the first segment of the ISS [14]. Financed by the U.S. and built by Russia, the control module had been plagued by delays. Two weeks later, the U.S. built *Unity* node was launched from a space shuttle (STS-88) and docked with *Zarya*. Following another two-year delay, the Russian developed *Zvezda* Service Module was launched and docked with *Zarya-Unity*. The service module provided a central hub to the ISS with engines, docking ports, life support, and living quarters [14]. Its addition enabled the station to be permanently inhabited by a crew. In October 2000, Expedition One crew entered the ISS, marking the beginning of continued human habitation in space.

The following years saw continued crew residencies and module additions of laboratories, nodes, Canadarm 2, trusses, and solar arrays. However, the *Columbia* shuttle disaster resulted in a two-year stand down of ISS construction and downsizing of the final station plans. After shuttle launches restarted in 2005, additional modules from the partner countries and support structures were added until the main ISS construction was completed in 2011 [14]–[16].

The ISS program has been an enterprise over 30 years in the making. Bringing the program to fruition depended not only

on the technical expertise and capability to design and build spaceflight hardware, but also the leadership of driven individuals, international commitment, and the nature of funding governmental space programs. The leadership and focus of individuals like Beggs, Mark, Hodge, Pedersen, Finarelli, and Rye secured presidential endorsement at the onset of the program while also tactfully addressing national security concerns. The efforts of subsequent NASA leaders, particularly Dan Goldin, played a significant role in maintaining funding for the project as it advanced from a development project to NASA's next major project in human spaceflight. The inclusion of international cooperation at the very beginning of space station planning enabled the program to utilize foreign funding and capabilities in development and also provide a layer of programmatic protection in the form of preserving America's reputation at the international stage. By taking advantage of early endorsement from top policy officials and fostering relationships biased towards continued cooperation among technical experts across borders, the ISS program leveraged international engagement for its continued development [6]. Although the funding mechanisms within NASA and among ESA member states often put the ISS program at the peril of Congress, such mechanisms paradoxically also ensured the space station's continued development, lest the economic throughput of certain states and the international standing of America to lead in human spaceflight be put at stake. These socio-technical influences drove the completion of the International Space Station and continue to influence the ecosystem in which the ISS operates as the major microgravity research platform.

3. CURRENT STATE OF MICROGRAVITY RESEARCH ECOSYSTEM

ISS

Since the arrival of Expedition One in 2000, the ISS has enabled continuous human presence in outer space. The size of a football field, the ISS orbits the Earth about every 90 minutes and offers opportunities for microgravity research, space exploration technology demonstration, and international engagement. The ISS consists of two main sections - the Russian Orbital Segment (ROS) that is operated by Roscosmos and the U.S. Orbital Segment (USOS) that is operated by NASA, the Canadian Space Agency (CSA), ESA, and the Japan Aerospace Exploration Agency (JAXA). Within ROS, Roscosmos tends to maintain 2-3 cosmonauts and within USOS, the partner agencies maintain 3-4 crew members. The ISS is supported by ground facilities for launch, operations, and payload services in the United States, France, Netherlands, Germany, Russia, Kazakhstan, and Japan. Visiting crew and cargo vehicles (governmental and commercial) hail from Russia, Japan, and the United States. In the past years the ISS has played a role in Earth observation, commercial space economic development, STEM education and outreach, and research in human physiology, material science, and robotics [17].

Internal facilities and laboratories support long-term research in a microgravity environment and external research platforms enable testing in the extreme conditions of outer space. Research facility use and crew time allocations are dependent on the partner agency that provided the physical facility and crew time allocation agreements. According to Article 5 of the IGA, "each partner shall retain jurisdiction and control over the elements it registers and over personnel in or on the Space Station who are its nationals." [13]. The MOUs the U.S. signed with each of the partner agencies allocate more complex utilization allocations of USOS [18]–[20]. The allocation distributions for the ISS are shown in Figure 1. RSOS is under 100% Russian ownership and utilization, with the exception of U.S. owned Zarya module. USOS is under mixed ownership and utilization. [17]–[20]. Partner agencies utilize their allocations for research in biology and biotechnology, earth and space science, human research, physical science, and technology demonstration [16].

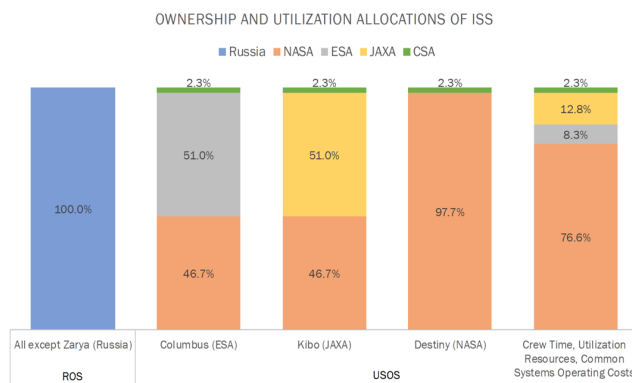


Figure 1. Ownership and utilization allocations of the ISS. With the exception of the U.S.-owned *Zarya* module, ROS is owned and utilized by Russia. *Columbus* was provided by ESA, *Kibo* was provided by JAXA, and *Destiny* was provided by NASA. The utilization allocations for these USOS modules are shown with NASA in orange, ESA in gray, JAXA in yellow and CSA in green. The allocations for logistical resources and costs are shown on the far right.

In 2005, the U.S. segment of the ISS was designated a National Laboratory to increase utilization of the lab by other Federal entities and foster commercial interest in conducting ISS research. In 2010, the NASA Authorization Act directed NASA to work with a nonprofit organization to manage 50% of the Agency's available research resources on the ISS via a cooperative agreement notice [21]. In August 2011, NASA signed a cooperative agreement with the Center for the Advancement of Science in Space, Inc. (CASIS), and dedicated \$15 million annually to manage all non-NASA research on the ISS [22]–[24]. Since 2011, CASIS has selected more than 200 non-NASA research projects from government, academic, non-profit, and commercial users. The projects range in the disciplines of life sciences, physical sciences, technology demonstration, remote sensing, and education [25]. Although CASIS has progressively seen

growth in the number and diversity of its users, it has faced recent management criticism regarding proper utilization of ISS resources as set forth in its cooperative agreement with NASA [24].

Beyond direct partner agency research and grants from CASIS, research on the ISS has recently been facilitated by commercial partners like NanoRacks. In 2009, NanoRacks signed a Space Act Agreement to self-fund their own research hardware and facilities as part of the U.S. National Lab and to market those facilities commercially [26], [27]. The firm operates as an implementation partner with CASIS and also facilitates projects with its own users. The firm's products include internal ISS payload platforms, satellite deployment from the ISS and Cygnus cargo vehicle, and the NanoRacks External Platform (NREP) mounted on the Japanese Experiment Module Exposed Facility.

Projects from non-ISS partner agencies currently have limited options for direct access to ISS research. In this context, partner agencies essentially act as gatekeepers. For organizations from countries that were not ISS partners, access to the ISS must be facilitated by a partner agency and the organization must work within the legal and logistical conditions set by the partner agency. For example, CASIS's portfolio of users is almost entirely U.S.-based. Organizations like the United Nations Office for Outer Space Affairs (UNOOSA) have facilitated agreements to broker access for non-spacefaring countries to conduct ISS research. The KiboCUBE program with JAXA aims to provide institutions from developing UN member state countries the opportunity to develop, manufacture, and deploy cube satellites from the ISS *Kibo* [28].

Other Microgravity Platforms

Beyond the ISS, other platforms currently available for microgravity research become more ground-based. Drop towers can be utilized to simulate extremely brief (less than 5 seconds) sessions of microgravity. UNOOSA is running its sixth cycle of partnership with the Center of Applied Space Technology and Microgravity (ZARM) in Bremen, Germany to offer student research teams from UN member states the opportunity to conduct experiments in the ZARM drop tower [29], [30].

Parabolic flight offers slightly longer microgravity sessions, the ability to simulate different gravity levels, and the capability of deploying a human-tended experiment without having to go to space. There are many military planes capable of flying parabolic maneuvers around the globe, but civil and commercial opportunities remain limited worldwide. In the U.S., ZeroG Corporation is the only commercial parabolic flight operator. The firm utilizes a modified Boeing 727 aircraft to offer parabolic flights for entertainment and research purposes to customers foreign and domestic. In Europe, Novespace - a subsidiary of the French space agency CNES - manages scientific flights on an Airbus A310 aircraft for space agencies, research groups, and occasionally

entertainment customers [31]. In Russia, microgravity flights have been offered for entertainment purposes out of Star City in a Ilyushin 76 MDK jet that has been used for cosmonaut training [32].

Suborbital space also offers the capability of short-term microgravity research. Blue Origin currently offers commercial, research, and education payloads slots on suborbital test flights of the New Shepard rocket. The project is currently under development for crew integration to extend capabilities for entertainment and human-tended experimentation [33]. High altitude balloons have also been used for short-term experiments, but the free fall state for payloads is difficult to control. Sounding rockets also offer the opportunity to fly payloads in extended, but not permanent, microgravity environments.

Microgravity research satellites have been developed to varying degrees around the world. China has launched research satellites with return sample capabilities and has collaborated with ESA in developing payloads [34], [35]. The Indian Space Research Organization (ISRO) has launched and recovered microgravity research satellites [36]. Commercial companies like SpacePharma also offer CubeSat platforms and integration services for automated pharmaceutical and medical device research [37].

The Chinese *Tiangong* program produced the *Tiangong-1* and *Tiangong-2* space stations which were utilized for crewed visits, microgravity research, and technology demonstration [38]. These stations were not permanently human-tended, but their construction enabled testing of docking procedures for future spacecraft planning. In April 2018, it was confirmed that *Tiangong-1* re-entered Earth's atmosphere in an uncontrolled descent and the Chinese space agency has confirmed that *Tiangong-2* will have a controlled de-orbit in July 2019 [39], [40].

4. CURRENT PROPOSALS IN THE MICROGRAVITY RESEARCH ECOSYSTEM

ISS Operations

In the past decade, the operational life and U.S. directed funding for the ISS has been repeatedly extended. Currently NASA spends about \$3 - \$4 billion annually to maintain and support ISS operations [17]. The 2018 U.S. President's Budget Request proposed ending direct federal support of the ISS in 2025 with the goal of turning operations over to commercial entities and increasing growth in a commercial Low Earth Orbit (LEO) economy [17], [41]. Feasibility studies analyzing what such a commercial LEO economy would look like are currently underway, but it is difficult to predict. For example, the hardware of the ISS will eventually reach the end of its lifetime, and crew time will become increasingly allocated towards space station repairs and maintenance. Beyond the technical issues involved, there are the social and logistical issues involved around ownership. While the U.S. does maintain a majority of the operations and

resource utilization allocations for USOS, it does not own all the modules. ESA maintains ownership over the Columbus module and JAXA maintains ownership of the Kibo module, to which NanoRacks's NERP is attached. Additionally, CSA owns Canadarm 2, which has been essential for station construction, maintenance, and EVAs. Logistically, the IGA and MOUs the U.S. signed with partner agencies in 1998, have become more intricate as each partner agency has brought in agreements with their own partners via multilateral organizations like UNOOSA and commercial entities.

Symbolically, the ISS has been utilized as an emblem of international cooperation and human ingenuity by not just ISS partner agencies, but communities all around the world. The image of the ISS disintegrating towards Earth in de-orbit, controlled or otherwise, may not only symbolize a break in continuous human presence in space but also affect the sentiment of international cooperation. Embedding international cooperation at the beginning of the planning and life of the ISS offered it a layer of insulation from U.S. congressional cuts in the 1990s. Given recent statements from U.S. leadership about the motivation to maintain America's leadership in space, it's possible that international prestige may again play a role in determining the fate of U.S. involvement in the ISS.

Other Proposed Platforms

In the midst of this uncertainty among ISS partner agencies, non-ISS partners, and commercial entities have begun to propose their own space stations. Some proposals depend on the ISS as a starting point, either through technology demonstration or as a docking point to begin construction of a new station. Bigelow Aerospace currently has its Bigelow Expandable Activity Modules (BEAM) attached to the space station as an expandable habitat technology demonstration for reducing transport volume for future space missions [42]. Based off of this technology, the firm has also proposed standalone space stations called B330s and announced a spinoff company to run its space station operations [43].

Russia has proposed the Orbital Piloted Assembly and Experiment Complex (OPSEK) as a third-generation modular space station in LEO. Since the ROS is still awaiting delivery of more Russian modules, including the *Nauka* laboratory, OPSEK could utilize these modules instead. Although OPSEK was initially proposed to be built off of current ROS elements once ISS retires, extensions of the ISS's operational lifetime have spurred discussions that OPSEK will be an entirely new station launched to a higher latitude that will enable Earth observation of Russia [44], [45]. Commentary by the Roscosmos head in 2017 also suggests that currently there are no plans to separate the ROS segments of the ISS and instead plans for future LEO stations should consider different management and investment structures to make it more efficient [46].

NanoRacks has proposed operating space station outposts by utilizing spent upper stages of rockets like ULA's Vulcan

Centaur or the Space Launch System. The firm is part of NASA's NextSTEP effort to conduct a feasibility study and has proposed that its outposts could either attach to the ISS or be free-flying. NanoRacks currently has a customer base from its payload integration products and was recently awarded a grant from NASA to study the future of human spaceflight in LEO [47].

Axiom Space, led by veterans of NASA's ISS program, has proposed a space station geared towards entertainment and space tourism. Plans call for assembly while attached to the ISS and separation once the ISS retires. Launch of the system is currently dependent on whether NASA awards the firm a dock to begin construction, after which funding rounds may continue [48].

The China Manned Space Agency (CMSA) has partnered with UNOOSA to solicit applications to fly experiments on-board the planned China Space Station. Any UN member state may apply. Designs for the China Space Station may have derived lessons learned from the *Tiangong* program and documentation from the UNOOSA solicitation detail station structure, experimental hardware, and proposals for basic configuration assembly by 2022 [49], [50]. Additionally, UNOOSA has partnered with the Sierra Nevada Corporation (SNC) to fly experiment payloads oriented towards the Sustainable Development Goals on SNC's developing Dream Chaser space vehicle [51].

5. FRAMEWORK FOR EVALUATING CURRENT AND FUTURE MODELS OF THE MICROGRAVITY MARKETPLACE

In considering future scenarios that may define access to operations in LEO, especially for microgravity research, the current marketplace must first be contextualized in light of its history and accessibility. The ISS is currently the major microgravity research platform and in different dimensions it can be perceived as multi-use, multi-partner, non-commercial, and nationality-based.

Multi-use platform—The International Space Station is a large scale, multi-purpose infrastructure that provides capabilities for a variety of activities. It hosts fundamental scientific research, applied research for product development, visits from space tourists, research projects focused primarily on education, earth observation platforms, and capability for launching small satellites. Some of these uses were anticipated during the early stages of developing the ISS, however, new opportunities and applications have been identified since ISS construction was completed. The modularity of the ISS and later standardization of its docking ports facilitates the introduction of new hardware and activities that were not envisioned in the original design.

Multi-partner Platform—Because of the large physical and financial scale of the ISS project, long term political strategy was needed by champions from NASA and their partners to

maintain government funding. To some extent, the ISS was successful because of the geopolitical context during the years in which key decisions were made. For example, the ending of the Soviet Union gave the United States an incentive to invite the Russian Space Agency to participate in a peaceful project that focused U.S.-Russian relations in a positive direction. In addition, the ISS project and the precursor projects allowed the United States, Canada, Europe and Japan to develop relationships, technical agreements and operational procedures for working together on complex space projects over multiple decades.

Non-commercial or quasi-commercial Platform— Another element of the International Space Station, from the U.S. point of view, is that it is operated as a public research utility due to the decision to make the U.S. segment a national laboratory. This decision implies that the government has an incentive to increase the use of the capacity on the research facilities by U.S. companies, universities, and government researchers. Thus, a higher priority is placed in utilizing the capacity of the research platform than on monetizing the capability. As CASIS works with organizations to facilitate their use of the U.S. National Laboratory facilities, they are evaluated based on the level of utilization of the physical capacity, launch capacity and astronaut time that is made available to them. It is worthwhile to note that they are not evaluated on the amount of revenue generated. Instead CASIS and NASA work to foster new research findings by U.S. companies and academic organizations that could lead to increased competitiveness. Commercial companies such as Nanoracks and Space Tango do seek to generate profit by charging customers to provide the services that will help them place research on the International Space Station. CASIS has gradually moved toward increasing the number of microgravity service providers with which they partner. Thus, they seek to foster an emerging industry of companies that can provide microgravity industry. Even with this quasi-commercial approach in which research customers pay a service provider to access the ISS, they are still using a public utility. The company is just reducing the workload of the customer to access this utility.

Nationality-based Platform—The current International Space Station is operated by a group of countries and the multi-lateral European Space Agency. As noted above, nationality plays a large role to determine which researchers and ISS users have access. In some sense, the ISS is highly open because many researchers, educational institutions and companies are able to partner with an entity from an ISS member country and thus access the platform. It is still true, however, that not every potential researcher or ISS user is able to readily establish a relationship with an eligible partner. Thus, the nationality-based access process does play a role in limiting global access to microgravity research.

It is unclear the extent to which the next generation of post-ISS microgravity research platforms will continue the patterns set by the ISS. Will the future platforms also be multi-use, multi-partner, non-commercial, and nationality-

based? Metrics can be used to rate future scenarios to designate whether they foster increased or decreased openness to new countries or organizations participating in microgravity research. This paper proposes that openness can be assessed along the two dimensions of economic openness and administrative openness. Economic openness refers to the extent to which a future microgravity marketplace has high costs of access. Administrative openness refers to the type of gatekeeping that determines who can participate, which may include access based on features such as nationality, type of organization, or type of microgravity activity. The authors assume that after the retirement of the ISS in its current form, there may be a mix of microgravity platforms that include fully commercial, public-private partnerships, and government-operated facilities. Among the government facilities, there may be a mix of single partner and multi-partner microgravity platforms. This discussion also assumes that some future microgravity platforms in LEO will be multi-use and other will be single use; thus, some may focus only on tourism while others mix leisure activities with research. It is impossible to predict the exact configuration that future LEO microgravity platforms will take, but this discussion considers a few representative scenarios and rates them according to economic and administrative openness, using the framework shown in Figure 2.

Fully Commercial Microgravity Marketplace

In this scenario, future microgravity research platforms are only operated by commercial actors. This case is likely to be high in administrative openness and low in economic openness. Here the assumption is that researchers from any nationality are allowed to pursue access to the microgravity platforms. This case also assumes that the commercial operators seek to generate profit by selling both services to prepare the research as well as for access to the physical platform. In this case, the physical platform takes on some of the characteristics of “real estate” that can be rented, leased or purchased. It is conceivable that the prices of this real estate on microgravity platforms could be determined by market forces, fluctuating similarly to real estate on Earth. These prices may be sensitive to the changes in supply and demand as microgravity capacity increases or declines. Moreover, these dynamics would be new in the microgravity research setting. It is possible that this would be a burden to academic researchers in general, particularly to those from countries that have not participated actively in microgravity research in the past. Economically, academic researchers may be concerned about affording the access to these platforms. Would government agencies play a role to stabilize supply and demand by purchasing microgravity real estate and offering subsidized access to researchers from their country? In that case, the marketplace becomes quasi-commercial and quasi-public. This pattern is currently visible in the U.S. case as NASA helps universities by giving them

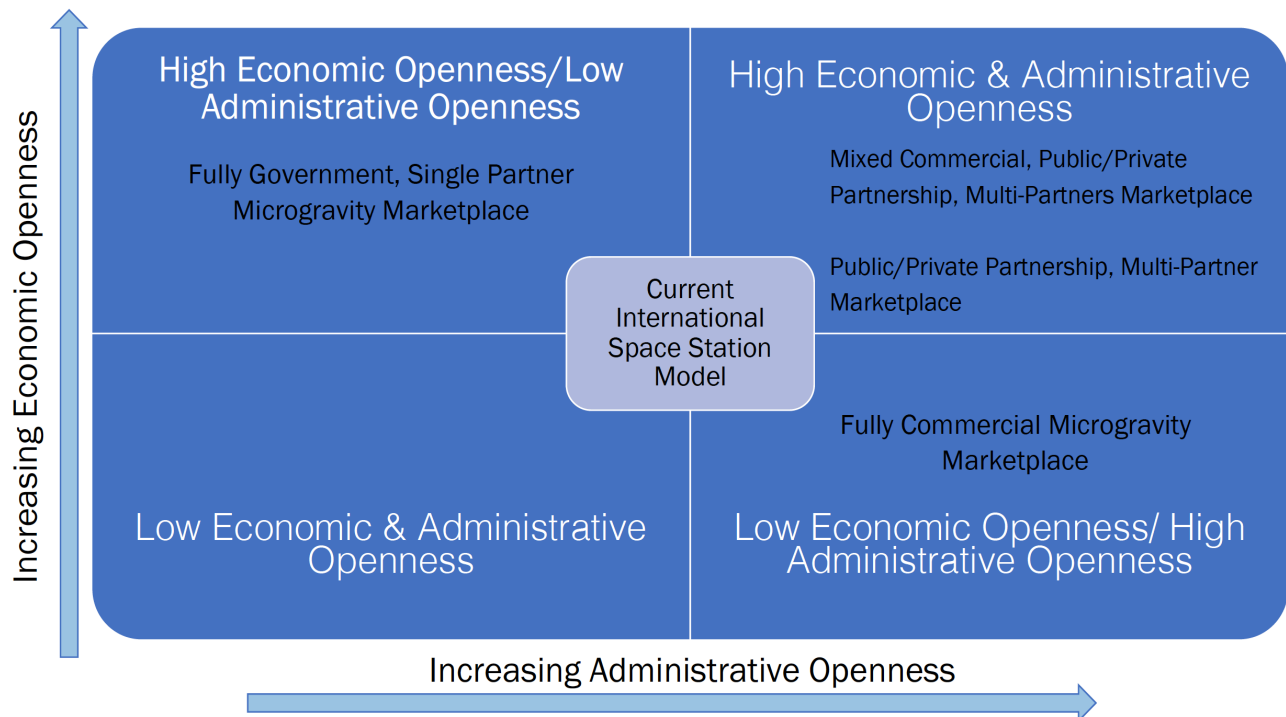


Figure 2. Proposed framework to evaluate models of the microgravity research marketplace along the dimensions of economic and administrative openness. The current ISS model is shown as a reference point at the origin. Future marketplace models are mapped in relation to whether they increase or decrease openness in comparison to the current marketplace.

grants to use commercially provided suborbital services for rocket launches, balloons and microgravity flights.

Fully Government, Single Partner Microgravity Marketplace

If the future microgravity marketplace is full of smaller scale, microgravity platforms owned by individual governments, the marketplace is likely to see an increase in economic openness for researchers from those countries and a decrease in administrative openness. These countries are likely to allow only organizations from their nations and partner nations to have access. Since the current ISS was built in part by international pressure from agreements that countries did not want to break, it is not clear whether a large number of individually owned government platforms is feasible. Meanwhile, the lessons from the International Space Station facilitate the possibility that individual countries can now propose small scale space stations with enough capacity for limited research. China has demonstrated that this is feasible.

Public/Private Partnership, Multi-Partner Microgravity Marketplace

A multi-partner marketplace in which several international teams build facilities based on public private partnerships is most likely to maintain the level of economic openness and administrative openness that is seen today. In that case, it will be difficult for many new space nations to have in-depth participation in microgravity research. However, emerging space nations might be able to contribute to platforms in a capacity similar to that of Canada during the development of the ISS. If those nations are currently undertaking capacity-building activities, such as those facilitated through UNOOSA collaborations, they are also developing technical expertise and trust between current ISS partner agencies. These collaborations hark back to the post-Apollo partnerships between the U.S., Canada, and Europe that facilitated cooperation on ISS development and could promote the inclusion of emerging space nations in the future marketplace.

Mixed Commercial, Public/Private Partnership, Multi-Partners

Perhaps the most likely outcome of the new microgravity marketplace evolution will be a mix of commercial and public/private partnerships that pursue multipurpose platforms. The commercial platforms increase administrative openness if they allow participants from all nations; and the public/private partnerships provide a minimum level of economic openness if they do not charge high costs for participants from their nations. There is still a concern, however, that some countries will not be members of the public/private partnership and will not be able to afford the commercial prices. In this case, there will still be researchers who face low economic and administrative openness. In order to address this, efforts must be increased to create public/private partnerships on a multi-partner basis with countries from all levels of space experience. This will help to ensure that new space countries have an opportunity to

influence the administrative policies of the future microgravity marketplace.

6. SUMMARY

Analysis of the history behind the ISS development identified factors of committed leadership and international engagement as influential to not only the planning of the ISS but execution of its deployment. The ISS and other current microgravity platforms provide a variety of research opportunities for user bases across the world. In the midst of discussions about how this ecosystem might change in the future, there have been a variety of proposals from commercial and governmental organizations for future microgravity platforms. However, neither the current state of the microgravity research ecosystem nor proposed platforms completely succeeds in enabling access to microgravity irrespective of nationality or economic status. Future work will apply the proposed framework to analyzing prior, current, and future microgravity platforms and identify dynamics that may influence increasing accessibility and sustainability.

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