OUR TEAM

We are an interdisciplinary collection of graduate students, researchers, staff and faculty working on space exploration at the Massachusetts Institute of Technology (MIT). MIT has a long and close connection to our nation’s space endeavors. We wish to thank you for your invaluable work as we transition into a new presidential administration, and to also bring to your attention certain issues before NASA and the Department of Commerce that we believe are key to the future success of the US government’s space efforts.

We are happy to assist with any further inquiries on these important issues and can be contacted at spacepolicy2020@mit.edu.

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This report encompasses several key topics for the incoming administration. The information is organized into two sections: 1) policy summaries and recommendations and 2) detailed reports. The detailed reports are provided as an appendix for further reading on a number of topics that our team specializes in.

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NASA

Earth Science and Climate Change Resilience

To advance the Biden administration’s goal of combatt[ing the climate crisis, NASA must continue to develop and support missions to understand the climate and must further integrate data and analyses from the private sector in efforts to monitor Earth. Additionally, NASA must both protect its existing infrastructure from the harmful effects of climate change and increase efforts to assess and mitigate the impact of its own activities on the environment. Our team recommends that NASA:

1. **Continue to pursue critical Earth science and climate missions that will help our nation understand, mitigate, and adapt to climate change** and its resultant impacts on our society. Specifically, we want to highlight:
   a. The CLARREO Pathfinder mission. This mission is key to accomplishing the National Space Policy goal to conduct “environmental monitoring and prediction;” it will provide a crucial calibration reference standard to inform policy decisions on climate change. This mission has been included in two consecutive decadal surveys.
   b. The PACE mission. This mission would provide information on how the ocean and the atmosphere exchange carbon dioxide as well as collect data on the extent and duration of harmful algal blooms. This mission was also recommended by previous decadal surveys (2007 and 2017).

2. **Continue and expand public-private partnerships for Earth observation and climate science.** The rise of commercial operators of satellite constellations has made an abundance of data available, but more work is needed to integrate it into the research environment. In particular, we encourage continuing to pursue the following programs:
   a. The Commercial Smallsat Data Acquisition Program (CSDAP). This program has made commercial satellite data available to NASA-funded researchers and has built a process for evaluating the utility of specific datasets. This encourages experimentation and the development of tools for processing this data.
   b. Continue to collaborate with Google Earth Engine (GEE) to make NASA data available on this cloud platform. This dramatically reduces data browsing, acquisition, mosaicing, and processing costs for researchers and other users of the data, both in terms of time and in terms of personal hardware. While many of NASA’s datasets are already available on GEE, many are not, including daily nightlight data from the VIIRS Day/Night Band, a product that has been important for studying coronavirus-related societal changes.
c. **SERVIR** – through which NASA partners with developing nations to improve access to earth observation data for applications in areas such as food security, disaster risk reduction, and climate resiliency. As NASA considers commercial acquisition of satellite data, it should continue to adopt a policy of open access to datasets and encourage broad geographical coverage for international partners reliant on data traditionally provided by NASA or NOAA.

3. **Pursue increased funding for climate adaptation measures to protect crucial space launch sites and infrastructure**, such as:
   a. Vandenberg Launch Complex. A [DoD report](#) states that in September 2016, a wildfire came close to Vandenburg launch complex, prompting the delay of a scheduled rocket launch. The report acknowledges that “climatic factors...can lead to an increased severity of wildfire activity.”
   b. Cape Canaveral Air Force Station, which is at risk of future climate-related flooding. Damage from flooding would be costly and setback space launches.

4. **Increase efforts to assess and mitigate the environmental impact of space activities.** Space-based technologies are critical for environmental protection and climate action, but the environmental impact of such activities – such as stratospheric emissions from launch vehicles – are still poorly understood. Therefore, we encourage the following approach:
   a. **Create a research initiative to better characterize the environmental impact of space missions.** Moving forward, NASA Environmental Impact Statements (EIS) should be based on complete life cycle assessments, which require accurate models. However, these do not exist today for every aspect of space missions. NASA should first identify high-priority research areas (such as global atmospheric models for launch and reentry) and fund research to fill these gaps.
   b. **Review NASA mission design methodology to include environmental considerations from the start.** Currently, environmental performance is handled as a constraint throughout the project life cycle and is evaluated as part of infrequent milestones. Instead, environmental performance should be a guiding principle in the design process. NASA’s leadership in designing such a methodology could be beneficial in establishing frameworks for the broader space industry.
Human Exploration and Operations

To advance human space exploration, NASA must reduce the cost of maintaining a human presence in LEO to allow allocation of resources towards deep space exploration. In efforts both in LEO and deep space, the US must maintain and strengthen international partnerships to share costs and ensure mission continuity. Our team recommends that NASA:

1. **Maintain a human presence in low Earth orbit (LEO) to accomplish human research goals while pursuing paths to allocate more NASA resources to future deep space exploration missions.** Specifically we encourage the following approach:
   a. **Extend the International Space Station (ISS) beyond 2024 to accomplish critical human research objectives.** In order to prepare for exploration missions beyond LEO, critical microgravity human research objectives focused on astronaut survival and function during long duration deep space travel must be accomplished. *These research efforts will extend beyond 2024*, and the ISS is currently the only platform with which to accomplish these objectives.
   b. **Pursue options for more cost effective future platforms in LEO to facilitate allocation of funds for deep space HEO efforts.** While the ISS currently facilitates important research, the estimated $3-$4 billion required annually to maintain the platform detracts from cislunar and deep space exploration efforts, as noted in the *2018 OIG report on the ISS*.
   c. **Facilitate commercial utilization of the ISS to diversify revenue streams and establish a self-sustaining LEO economy, where NASA is one of many customers.** Innovative companies and researchers have found success in utilizing the ISS; however, considerable barriers

*Tim McGrath and Jeremy Stroming of MIT AeroAstro test their microgravity rowing ergometer—a compact exercise device specifically designed for enclosed space habitats and crew cabins. Credit: Steve Boxall for MIT Media Lab Space Exploration Initiative.*
to entry remain for potential new users who may not have experience designing for a space launch or mission, or understand the benefits of the microgravity environment. To entice new users to the ISS, we recommend that NASA:

i. Expand communication about and advertisement of the ISS platform
ii. Develop protocols and best practices for potential customers that are new to developing payloads for the ISS
iii. Streamline NASA/CASIS management of the ISS National Lab as recommended in the 2019 Independent Review of the lab
iv. Set measurable targets for performance (i.e. achieving 30% of commercial use by 2025).

2. Maintain and strengthen existing international collaborations while pursuing new opportunities for international collaborations in human space exploration. Specifically we encourage the following approach:
   a. **Provide assured program longevity for long-duration missions, including reaffirming the Artemis Accords**, to alleviate international concerns of changing exploration goals between administrations. Many of NASA’s international partners maintain space program goals 5-10 years out, creating challenges in committing to NASA programs that could be altered or cancelled during this timeframe.
   b. **Continue existing international collaborations and expand the number of international agreements focused on human spaceflight.** Shared responsibility for new technology development can reduce costs for future exploration missions. Only 16% of international agreements (as of 2015) focus on human spaceflight and operations. Encouraging funding partners to invest in human exploration could reduce some domestic development costs and provide a visible demonstration of strong international cooperation.
   c. **Pursue opportunities for collaboration with China in civil space.** The US is alone in not collaborating with China in civil space via the Wolf amendment (Sec 526) continues in spite of China’s rise as a space power. The US is at risk of being left out of ongoing and future human spaceflight collaborations, such as joint astronaut training efforts between ESA and China, and potential collaborations between China, Roscosmos, and ESA on a lunar research station. Examples of US-China collaboration in space already exist, such as the recent collaboration between NASA’s Lunar Reconnaissance Orbiter on China’s robotic lunar landing of Chang’e-4. Additionally, NASA Administrators Bridenstine and Bolden have been supportive of further collaboration with China in civil space.
Ensuring Economically Viable Lunar Settlements

Returning to the lunar surface is the next great step for human space exploration. Lunar and cis-lunar space present untapped opportunities for scientific discovery, economic growth, and long-term off-world human settlement, as well as a gateway to Mars and beyond. In April, NASA released their Plan for Sustained Lunar Exploration and Development, which identifies the foundational capabilities required for this next great step in space exploration. In July, the American Institute of Aeronautics and Astronautics (AIAA) held a workshop with more than 200 industry participants to discuss and respond to NASA’s plan. Participant input was used to write a summary report (titled “Ensuring Economically Viable Lunar Settlements: Proceedings Report” and provided in the appendix) that examines the technological gaps, economic conditions and information gaps that must be addressed to realize the dream of a self-sustaining and economically viable lunar settlement, as well as the role of national space agencies, governments, and industry in addressing these conditions.

Technology Gaps: Long-term lunar settlement presents significant challenges to human and robotic exploration. Workshop participants identified the following technology gaps that need to be filled:

- **In-situ resource utilization**: detect, map, extract, process & utilize water, gases & minerals
- **Earth-independent habitation systems**: food, water, life support, waste, radiation shielding
- **Low-cost transportation**: reusable spacecraft, in-space refueling, landing pads, new propulsion
- **Astronaut health**: mitigating risks from radiation, microgravity, dust; artificial gravity
- **Power systems**: large-scale solar and nuclear; power beaming and storage; portable power
- **Communication & navigation**: a lunar position, navigation, timing and communication system

Left: Rendering of MIT’s Multifunctional Expandable Lunar Lightweight Tall Tower (MELLTT), a lunar tower concept that was developed to TRL 4 through funding from NASA’s 2020 BIG Idea Challenge. Right: Artist’s conception of MELLTT on the lunar surface.
• **Space systems:** easily upgradeable; long-lived; radiation-hardened, thermal, vacuum & dust
• **Interoperability and standardization:** interoperable systems essential for transactions in space
• **Autonomy and telerobotics:** labor force multiplier, supporting all maintenance and exploration

**Economic Conditions:** Long-term economic sustainability requires private capital to meet the rising costs of maintaining growing settlements and ongoing technology development. There are several economic preconditions for this, including the government nurturing the emergence of physical, social and legal infrastructure; the government serving as the first customer to open the door to private investment; maintaining a clear motivation; understanding and balancing stakeholders needs; establishing accessible transportation and robust logistics; and investing in key technology developments that will support commercial activity.

**Information Gaps:** In order to advance sustainable economic conditions on the Moon, stakeholders need access to reliable and accessible information. There are several key information areas that require more data collection or definition: lunar resources, innovative business cases and market development, consensus rules of engagement, scientific research, strategic planning, and delineation of relationships.

**Non-Aerospace Sectors:** Given the diversity of expertise and capability required for lunar settlement, it is crucial to engage commercial and governmental sectors outside of traditional aerospace. This will ensure long-term economic viability and decrease technology development times. The following sectors were identified as crucial to engage for the next 20 years of lunar development: healthcare, mining and construction, waste and water management, agriculture, manufacturing, education, tourism, telecommunications, and the energy sector.

**Role of US Government (USG):** Workshop participants identified predictability and institutional certainty as key conditions. Transitioning from initial lunar landing to a sustained lunar settlement, USG should focus on paving the way for greater private investment through acquiring geological and environmental information on the lunar surface, developing regulatory and legal standards, offering long-term contracts for lunar development, and investing in education to ensure a highly qualified workforce.
This is a truly transformational epoch for the space sector. New technologies, business cases, and ideas are empowering the American entrepreneurial spirit to build new businesses and markets in space to benefit those here on Earth. The Department of Commerce (DoC) is well-poised to provide the necessary connective and supporting infrastructure to strengthen innovative new markets and ensure American economic leadership of a safe, sustainable space sector. We offer the following recommendations on certain space-related issues within the purview of the DoC.

1. **Continue progress towards implementing Space Policy Directive-3**: There has been significant debate over the last several years regarding the proper home for civil space situational awareness (SSA) and space traffic management (STM) activities within the federal government. Space Policy Directive-3 tasked the DoC with this role, a decision reaffirmed by a recent report by the National Academy of Public Administration and funding for a DoC STM pilot. The transition to civil provision of SSA and STM is urgently needed and overdue. The DoC should continue these efforts, including work to further develop the Open Architecture SSA Data Repository (OADR) and to encourage and facilitate U.S. commercial leadership in SSA, STM, and related science and technology.

2. **Establish the DoC Office of Space Commerce as a champion within the U.S. government for space sustainability research and commercialization**. During the Biden Administration, there will be a massive increase in the number of orbiting satellites, complexity of space missions, and density of space operations, a trend which has accelerated rapidly in the past decade. Strong U.S. government leadership is needed to ensure that Earth orbit remains safe and open for business, and that U.S. companies are at the vanguard of the emerging marketplace for space sustainability related services. We specifically recommend the following:

   a. **Seek authority and funding to establish one or more space sustainability centers of excellence** to foster the development of interdisciplinary space research to facilitate safe space operations with greater density, autonomy, and complexity. This would expand on the proposal for a Center of Excellence for Space Situational Awareness contained in the Space Preservation and Conjunction Emergency (SPACE) Act of 2020 (S. 4827).

   Topics like the economic costs of space

   Distribution of orbital debris around Earth in 2009. Image from NASA.
debris, orbit allocation, STM, and civil SSA are critical to assuring safe future space operations and smart regulation, but lack a clear home, funder, and champion within the U.S. government space enterprise. The explosion of commercial space activity is driving the need for such research and the products of these centers of excellence could infuse state-of-the-art academic results into OSC’s work on the OADR and other SSA/STM architectures and regulatory vehicles.

b. **Pursue measures to develop American leadership in active debris removal technology.** Key portions of low Earth Orbit are past the tipping point where active debris removal (ADR) will be necessary to stabilize the debris population and prevent runaway growth of the debris population. While pursuing development of ADR technology has been part of the national space policy of the United States for almost a decade, actual progress has foundered, as such work has neither been funded at adequate levels nor seen as a priority by either NASA or the Department of Defense (DoD). At the same time, both the European Space Agency and Japan have pursued contracts with private companies to accelerate commercial development of ADR capabilities and develop their own industrial base. The recently released National Orbital Debris Research and Development Plan jointly tasks the DOC, DoD, and NASA with developing technologies and techniques necessary for ADR. The DoC should seek funding and authority to promote the development of American commercial ADR activities and American leadership in a future ADR marketplace through various technology pull programs. The attached policy paper (titled "An Advance Market Commitment Program for Low Earth Orbit Active Debris Removal") proposes one possible program design to do so.

c. **Partner with NASA, the FCC, NOAA, the DoD, and others to develop and implement a comprehensive space environmental management plan.** Controlling the space debris problem will require both debris mitigation (to reduce the creation of new debris) and debris remediation (to remove current and future high-risk debris objects from orbit). NASA is the best home for much of the technical work to identify the mitigation practices and levels of adoption needed, as well as the quantity, timeline, and targets for ADR. A recent NASA Office of Inspector General report encouraged the agency to more actively pursue ADR technology in collaboration with national and international partners. The DoC can play a key role in facilitating the development of a robust industrial base to support both mitigation and remediation effort, and incentivizing widespread adoption by industry of responsible norms, best practices, and standards.
Continuity of Purpose: Advantages of Inspired, Sustained U.S. Leadership in the Lunar Domain

With the International Space Station approaching retirement within the next seven years, NASA stands at a critical inflection point in regard to its role in sustaining human spaceflight. With the Artemis program, the U.S. can once again play a leading role in convening the international community to take the next steps in space exploration and creating platforms and opportunities for the vibrant commercial space industry.

In order to secure the U.S. as a leader in lunar exploration, we recommend the following policies:

1. **Continue the Artemis Program.** In 2014, NASA announced its intention to return humans to the lunar surface by 2028 with the Artemis program. By leveraging a financially sustainable path to maintaining U.S. presence in low Earth orbit, NASA can increase investment in missions to the lunar surface and lunar orbit, demonstrating critical technologies and operational capabilities that will enable future Mars missions. With the Biden administration’s leadership, technologies developed for the harsh, resource-constrained environment of the lunar surface (e.g., advanced solar power systems, dust mitigation solutions, and more) can be adapted to also serve time-critical resilience and green-tech infrastructure in our fight against climate change. Let us follow in the great tradition of transformative NASA spin-offs from the Apollo era (including the Apollo Guidance Computer, developed at MIT, which led to significant advances in the computing industry and integrated circuit development), and shape the Artemis era in equal service to our citizens’ needs and our planet.

2. **Invest in commercial service providers to develop critical capabilities in the commercial space industry.** The Human Landing System (HLS), Commercial Lunar Payload Services (CLPS), and Gateway Logistics Services (GLS) contracts represent a new era of public-private partnerships for NASA. Based on the clear success realized just this past year from the Commercial Crew Program, continued commercial partnerships will allow NASA to contract services from private industry to achieve mission objectives while contributing to the development of a vibrant commercial space ecosystem and cis-lunar economy.

3. **Foster inter-agency cooperation for a coordinated U.S. space strategy.** We are once again at the cusp of great activity and dynamic evolution in the space industry. We need strong leadership and actively managed coordination to coalesce the many agency and department priorities involved—from NASA, to NOAA, Department of Commerce, FAA, DoE, DoD, NIH, NSF and more—into a powerful, unified American space policy. A coordinated inter-agency strategy makes our forays into the near and far reaches of space more efficient, more impactful, and longer lasting, which will in turn enable a return to the pioneer spirit in America as we take our bold and principled adventurousness from the Moon to Mars.
4. **Adopt a leadership position in coordinating the development of norms and standards for operation on the lunar surface and in cislunar space.** In the absence of strong regulations, norms, and standards, default precedent-setting will dictate early exploration activities. NASA should adopt a coordinating role in this regard, working with commercial providers to agree upon **standard interfaces for interoperability**, and inviting the broader international community to **develop standards** in shared platforms such as Gateway to reduce friction in use of the resource.

5. **Encourage open and free data and information sharing among lunar actors.** NASA has a long heritage of publishing mission plans (in accordance with **Article XI of the Outer Space Treaty**) and releasing subsequent datasets for use by the international community, a commitment reaffirmed in the Artemis Accords. NASA leads internationally in this regard, and still sets an admirable, worldwide bar for open-data and public coordination. At MIT, our **Lunar Open Architecture** aims to follow NASA’s leadership in this domain, and make lunar stakeholder mission data easily accessible in a comprehensive database to encourage collaboration among future lunar actors. NASA should encourage allies and partners in space exploration to adopt universal standards for data sharing and support best practices in publishing research results to further improve the fidelity and availability of information necessary to unlock future exploration. Well-informed, coordinated activity on the lunar surface can lead to more efficient use of constrained resources in a fledgling cislunar economy.

The space industry has been **mobilized and revitalized** by NASA’s decision to return humans to the lunar surface in the next decade. The **number of lunar actors** has seen a dramatic increase in just the past few years, and this trend will only continue if NASA is able to demonstrate continuity of purpose. Sustaining and building upon the Artemis program will cement NASA’s role in leading the international community into a new era of sustainable space exploration.

**Tools for Lunar Space Strategy Decision Making**
Review recent and planned lunar surface activity across the space industry, and read more opinions from leading space industry figures at our Lunar Open Architecture "**Council of Voices**" [full link: https://loa.mit.edu/#/CE]

Images of MIT's the Lunar Open Architecture.
The relationship between the United States and China in the space sector over years is complex. Initial collaborations between the two countries took the form of Chinese launch services for US communications satellites in the 1980s. However, entering the 2000s, the United States Congress has announced multiple bans against scientific and civil space collaboration with China due to various sources of concerns. One defining incident that affected the US-China space relationship is the Wolf Amendment that was introduced to the Commerce, Justice, Science, and Related Agencies (CJS) bill in 2011.

In the full-length paper on this topic (titled "The US-China Relationship in the Space Sector" and provided in the appendix), we outline the history of the US-China relationship in the civilian space sector, and address the "Wolf Amendment" with its impacts on the US, China and global space community. We also explore future policy recommendations in order to promote a more collaborative and less conflicting US-China space relations atmosphere in the civil space exploration sector. These policy recommendations range from revision to the Wolf Amendment for collaborations in certain fields, new bilateral agreement between the two countries, US Congressional champions, and enhancement of academic exchange.
Our key policy recommendations include:

1. With the understanding of the importance of the Wolf Amendment in US defense and national security space, **we recommend against a full repeal of the Amendment.**
2. Given the negative global impacts, as well as the administrative and political barriers that the Wolf Amendment has created, **we propose a revision to permit the existence of certain types of space collaboration** where interests are aligned between the US and China, in the areas of:
   a. Human spaceflight and lunar exploration missions
   b. Planetary and Earth science
   c. Space traffic management
3. We propose that any new agreement for US-China space collaboration shall have the following hard requirements for both sides to clearly understand and be willing to abide by:
   a. **Transparency**
   b. **Reciprocity**
   c. **Mutual benefit**
4. Understanding the US Congress’s processes, **we propose identifying key Congressional members** to champion international, civilian space collaboration and/or support an open and collaborative US-China relationship as one of their top three priorities among their legislative priorities.
5. Under the current political atmosphere, **we recommend prioritizing the protection of international students from China from immigration policies that might prevent them from studying in the US,** since academic training is the base for any future space collaboration and critical for the advancement of science towards global welfare.
About the Authors

As a Ph.D. candidate in the Harvard-MIT Health Science and Technology Program and a Draper Fellow, Rachel studies Medical Engineering and Medical Physics with a concentration in bioastronautics. Her current research with the MIT Human Systems Lab focuses on wearable technology for human spaceflight. Rachel is passionate about allowing humans to live and work safely in space and finding ways to translate space research to Earth applications. Rachel previously received a B.S. in Biomedical Engineering from the University of Rhode Island and has interned for the Naval Undersea Warfare Center Newport and the National Institutes of Health.

RACHEL BELLISLE

As a dual-degree M.S. student at MIT studying aerospace engineering and technology policy, Becca enjoys working with interdisciplinary teams to further humanity's exploration of space. Her current work incorporates engineering, policy and business to study the economic viability of commercial spaceports and to plan strategic science and technology goals for lunar exploration. A native Texan, she left her home state to get a B.S. in mechanical engineering from the University of Oklahoma. Becca spent two years in technology consulting and has interned with Boeing, Made In Space, and the Commercial Spaceflight Federation. She is also a 2020 Matthew Isakowitz Fellow.

BECCA BROWDER

Carson Bullock is a M.S. student in MIT’s Technology and Policy Program. Their work focuses on the role of international norms and the social meaning of space, and how norms might be leveraged to encourage sustainability, transparency, and peaceful use. They have collaborated with the MIT International Center for Air Transportation to produce cartography for social impact and with the Space Enabled research group to promote the just use of outer space resources. Carson holds a B.A. in Physics and Political Science from The College of Wooster, where they wrote their undergraduate thesis on orbital debris proliferation.

CARSON BULLOCK

Ariel Ekblaw is the founder and Director of the MIT Space Exploration Initiative, a team of >50 graduate students, staff, and faculty actively prototyping the artifacts of our sci-fi space future. Founded in 2016, the Initiative includes a portfolio of 40+ research projects focused on life in space and supports an accelerator-like R&D program for payload development and flight opportunities. Ariel earned a B.S. in Physics, Mathematics and Philosophy from Yale University and recently defended her MIT Ph.D. in autonomously self-assembling space architecture for future habitats and space stations in orbit around the Earth, Moon, and Mars. Ariel’s work has been featured in WIRED, MIT Technology Review, the Wall Street Journal and numerous other outlets.

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Dr. Richard Linares received B.S., M.S., and Ph.D. degrees in aerospace engineering from the University at Buffalo in 2009, 2011, and 2014, respectively. From 2015 to 2018 he was an Assistant Professor at the University of Minnesota before becoming a Charles Stark Draper Assistant Professor at the Massachusetts Institute of Technology in 2018. His research interests include astrodynamics, space situational awareness, satellite guidance and navigation, estimation, optimal control, and reinforcement learning. Dr. Linares received the DARPA Young Faculty Award in 2020.

Seamus Lombardo is an AeroAstro Ph.D. student conducting research in the Space Enabled Research Group at MIT. He uses remote sensing and integrated complex systems modeling to support sustainable development, with applications such as protecting Indonesian communities from coastal flooding. Seamus previously researched spacesuit performance and received his M.S. degree in MIT AeroAstro. He received his B.S. in Aerospace Engineering from SUNY Buffalo. He has interned throughout the space industry at Millennium Space Systems, SpaceX, and NASA. Additionally, Seamus is active in politics and advocacy through his work with MIT Graduate Student Council, MITvote, Bluebonnet Data, and MIT Democrats.

George Lordos is a Ph.D. student in MIT’s Department of Aeronautics and Astronautics, researching sustainable industrial ecosystems and human settlements on the Moon and Mars. George received a B.A. in Philosophy, Politics and Economics from the University of Oxford in 1991, a MBA from MIT Sloan in 2000 and a Master’s in Engineering and Management from MIT SDM in 2018. In between, George had a 25-year professional career as a system architect, entrepreneur, company director, and strategy consultant.
Dr. Dava Newman is the Apollo Program Professor of Astronautics at the Massachusetts Institute of Technology (MIT) and a Harvard–MIT Health, Sciences, and Technology faculty member. Her research in multidisciplinary aerospace biomedical engineering investigates human performance across the spectrum of gravity, including space suits, astronaut performance and space policy. A PI on 4 spaceflight missions on the Shuttle, MIR, and ISS, she is well-known for her second skin BioSuit™ planetary spacesuit, and her inventions are applicable to “soft suits/exoskeletons” to enhance locomotion on Earth. Her BioSuit™ museum exhibits include the American Museum of Natural History, Victoria and Albert Museum, Metropolitan Museum of Art, Venice Biennial, and the Chicago Museum of Science and Industry. Her latest research includes Earth Speaks™ – an open source platform of curated space data that applies AI and supercomputer visualizations to help accelerate actions to help regenerate Earth’s oceans, land and climate. Newman is the author of Interactive Aerospace Engineering and Design, has >300 publications, and has supervised 100 graduate students and mentored >200 undergraduates.

Benjamin Martell is a M.S. student in MIT’s Department of Aeronautics and Astronautics, conducting research in the Aerospace Plasma Group on the use of corona discharge for airplane lightning mitigation, isolated charge control, and Mars ISRU. Ben is also working to develop lunar tower infrastructure (called MELLTT) in a project that started as a NASA student challenge. Ben earned his B.S. in mechanical engineering from the University of Rochester.

Maya Nasr is a Lebanese Ph.D. student in the Aerospace Engineering department at MIT working on the Mars Oxygen ISRU Experiment (MOXIE) for NASA JPL’s Mars 2020 mission. She received her B.S. and M.S. degrees in Aerospace Engineering from MIT in 2018 and 2021 respectively. She is the Policy and Congressional Legislation Lead for the SGAC US Taskforce. She also leads the Space Weaponization, Space Ethics & Human Rights, and Space Resources subgroups with the goal of space disarmament and peaceful use of outer space. Her research interests are space systems, international space law, policy and politics, space security and disarmament.

Dr. Dava Newman served as NASA Deputy Administrator from 2015–2017, nominated by President Obama and unanimously confirmed by the U.S. Senate. Along with the NASA Administrator, she was responsible for the agency’s vision, leadership and policy direction, and representing NASA to the White House, Congress, international space agencies, and industry. Dr. Newman was the first female engineer to serve in this role and was awarded the NASA Distinguished Service Medal. She championed the human journey to Mars, technology and innovation, STEAMD (STEM+Arts+Design) education, and diversity and inclusion. Newman earned her Ph.D. in aerospace biomedical engineering, Master of Science degrees in aerospace engineering and technology and policy from MIT, and her Bachelor of Science degree in aerospace engineering from the University of Notre Dame.
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Appendix: Detailed Reports
STATEMENT OF ATTRIBUTION

This report is the outcome of the ASCENDxCo-Lab on Economically Viable Lunar Settlement held on 29 July 2020. It was drafted in August 2020 and approved for release by the AIAA Public Policy Committee in September 2020. More than 200 space industry leaders and experts participated in the virtual workshop, representing academic institutions, commercial enterprises, government agencies, and professional societies from around the world. This report reflects the collective views of the workshop participants and is not necessarily a position of AIAA at large.
EXECUTIVE SUMMARY

Return to the lunar surface is the next great step for human space exploration. Lunar and cis-lunar space present enormous opportunities for scientific exploration, economic growth, and long-term off-world human settlement, as well as a gateway to Mars and beyond. In April 2020, NASA released NASA’s Plan for Sustained Lunar Exploration and Development [1]. This plan outlines NASA’s three-domain exploration strategy – to return humans to the lunar surface in 2024, to lay the foundations of a sustained long-term presence on the moon, and to pave the way for crewed Mars exploration – placing the Artemis program at the core of NASA’s human spaceflight and exploration strategy for the next decade. While NASA’s plan identifies the foundational capabilities required, including habitation modules, surface mobility units, and an increased robotic presence, there are numerous technological gaps and economic considerations that must be addressed to realize the dream of a truly self-sustaining and economically viable lunar settlement.

In July 2020, as part of a series of events leading up to the inaugural ASCEND event, the American Institute of Aeronautics and Astronautics (AIAA) conducted the ASCENDxCo-Lab on Economically Viable Lunar Settlement, a collaborative workshop convened to discuss and respond to NASA’s plan [2]. This report presents a summary of the findings of the workshop, examining the technological and economic conditions that need to be established to move towards a sustained and economically viable lunar presence, as well as the role of national space agencies, governments, and industry in addressing these conditions. For this analysis, a sustained lunar settlement is defined as one that meets the test of continuous survival and operation over time, and an economically viable settlement is defined as one for which the long-term cost of the continuous investment in its maintenance is ultimately underwritten by private capital. This report was prepared by the authors but represents the combined inputs of more than 200 attendees.

TECHNOLOGY GAPS

NASA and its international partner agencies have spent the past 20 years successfully proving technologies to enable astronauts to live for months in low Earth orbit (LEO) aboard the International Space Station (ISS). However, shifting from temporary habitation of an orbiting laboratory to long-term lunar settlement requires the fielding of a variety of technology areas, many of which are currently at a low Technology Readiness Level (TRL). Workshop participants identified the following technologies as crucial for enabling an economically viable lunar settlement. Increasing TRL in these areas will ensure the settlement is not entirely reliant on Earth for resources, power, and capability, as well as providing potential business opportunities for commercial entities.

› In-Situ Resource Utilization (ISRU) – ISRU is one of the most frequently cited technology gaps when considering long-term space exploration and settlement. The goal of achieving economic viability on the moon is only possible if the capability exists to detect, extract, process, and utilize lunar resources. Large-scale resource mining for lunar regolith, water, and volatiles must be developed that can operate autonomously (or semi-autonomously) and in the harsh lunar environment. Autonomous processing and additive manufacturing capabilities will allow these resources to be utilized to build infrastructure and hardware components, life support, and agricultural systems, as well as fuel for surface and launch/landing transport systems. With such an unproven technology, it is vital that ISRU be a core component of NASA’s critical path to lunar settlement.

› Long-Term Habitation Systems – To enable a truly Earth-independent lunar settlement, habitation systems that do not rely on resupply from Earth for food and life support will need to be developed. This includes technologies for closed-loop or regenerative life support systems, crop growth and harvesting, water and waste processing and recycling, and improved radiation shielding. Habitats and infrastructure designed for lunar settlement should aim to be easily deployed, either through self-assembly or remote assembly via autonomous or telerobotic systems. Artificial intelligence provides a possible avenue for the management and maintenance of these habitats.

› Surface and Lunar Transportation Systems – Earth to cislunar, cislunar to lunar surface, and surface transportation systems will form a key component of any long-term lunar settlement. Reliable and low-cost Earth-moon transport and supporting infrastructure (launch and landing pads, refueling depots, etc.) are crucial to support Earth-moon-Mars supply chains and the transport of lunar residents. It is vital to raise TRL for low-cost reusable descent and ascent vehicles for the lunar environment, regolith stabilization to support multiple landings and launches, and alternative propulsion methods such as nuclear or electric propulsion.

› Human Health – The maximum time an astronaut has spent in a microgravity environment is 438 days. For lunar and Mars missions improved mitigation strategies for the known effects of microgravity should be investigated, and further investigation into the long-term effects of microgravity environments will be needed.

› Power Generation and Distribution – Currently the largest power generation in orbit, the 1 acre of solar panels aboard the ISS is capable of generating 84–120 kW. For comparison, McMurdo Station in Antarctica requires approximately 2–3 MW to operate heating and laboratories for ~1200 residents. A comparable lunar settlement is likely to have power requirements several orders of magnitude beyond current orbital capabilities, particularly with the addition of mining and transport equipment. Large-scale power generation via nuclear or solar power must be developed that can cope with the temperature extremes of the lunar day-night cycle, as well as support habitation, exploration, ISRU, and scientific research. Efficient and lightweight methods of power transmission, such as power beaming, and power storage and portability, are critical technologies that must be developed to enable large-scale, distributed lunar settlement and surface transport.

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Communication and Navigation Systems – While telecommunications and GNSS-reliant navigation systems are ubiquitous on Earth, no such capability yet exists on the lunar surface. A long-term lunar settlement will need a reliable, large-scale Position, Navigation, Timing, and Communications (PNTC) network to provide capabilities such as absolute positioning to within 1 meter to support surface exploration and transport, and communications analogous to cellular and internet services on Earth. Communications systems will need to support high-bandwidth transmissions to enable telerobotic operation of assets, video links, and timely transmission of data to Earth.

Robust and Reliable Hardware – The lunar surface is a harsh environment, and thus any lunar hardware will need to be highly robust and reliable, radiation-hardened, and designed to operate across the wide temperature range (4-400 Kelvin) of lunar day-night cycles or at the extreme low temperatures within permanently shadowed regions. Additionally, significant investment in lunar dust mitigation technologies is key, both for hardware and human survivability. Lunar regolith simulators of better quality and higher quantity will need to be developed to qualify flight systems for lunar operation. Additionally, given the long-term nature of a settlement, hardware should be designed for increased life spans, and/or the ability to be easily upgraded over time.

Interoperability and Standardization – A key technology gap moving forward with long-term lunar plans is developing interoperable space systems. Working with international partners and working across public and private sectors, technology interfaces and architectures will need to be standardized and have systems of systems that are compatible and able to exchange information.

Autonomous Systems and Telerobotics – Raising the TRL of autonomous systems and increasing the use of artificial intelligence in space systems will help to address some of the above technology gaps. A long-term settlement will likely rely on autonomous fault detection and maintenance systems to lessen the burden of work on human residents. In addition, highly autonomous robotic systems can aid in exploration, ISRU, and remote sensing.

The NASA plan makes it clear that the path for future lunar exploration has the ultimate goal of a long-term sustained presence; however, this will only occur “once [technologies and capabilities] of the moon to Mars campaign are delivered and operational [3].” Designing solely towards the goal of a 2024 lunar landing and a Mars landing in the 2030s, with little consideration for long-term lunar presence, could result in innovative but short-lived and small-scale technologies that do not effectively support a sustainable lunar settlement. When developing the technologies outlined in the plan – such as surface transport or habitats – durability, upgradeability, and scalability of these technologies need to be considered. For example, when evaluating concepts for a foundational surface habitat, designs should be selected that address the technology gap of interoperability and standardization, thus enabling future construction to be built upon existing infrastructure as more players arrive on the lunar surface. Long-term planning is required to ensure that each technology developed addresses the gaps outlined above and, ultimately, supports long-term settlement.

As noted in “The Role of NASA and its International Partner Agencies” section below, public sector funding and investment will be critical to filling these technology gaps. The award of long-term “anchor tenant” contracts is one way governments can provide the market certainty needed by industry to invest in these technology gaps.

**ECONOMIC CONDITIONS CONDUCIVE TO SUSTAINED LUNAR SETTLEMENTS**

The findings of this workshop highlight that the vision for a sustained lunar settlement is the emergence of a diverse space economic ecosystem over the long term. The development of commerce and industry in space is a key component of any long-term lunar settlement and the long-term economic success of such a settlement relies on several key economic conditions:

- Role of Government - NASA’s Plan for Sustained Lunar Exploration and Development and the findings of this workshop both highlight that there is an inherent role for the government in advancing lunar economic development. Governments can nurture the emergence of baseline physical, social, and legal infrastructure that will serve as a scaffold for private entrepreneurial activity in space. Government entities should support the development of commerce and industry in space through investment in space infrastructure, support for research and technology development, and promoting a secure and predictable environment in space. Among nations with space programs, those with strong economies are seen as most likely to support such investment and as the key early strategic partners for international collaboration, burden-sharing, and rulesetting. A thriving space economy will emerge only if space is open to free enterprise. Government, as the first but not the only customer, can steer technology development, buy down risk, and stimulate private investment in key capabilities in transportation, logistics, communications, energy, and habitation. In addition, the role of government should be carefully defined so as not to position the government to compete with private industry.

- Motivation – The establishment of any space settlement will rely on a key driver or socioeconomic motivation. Possible drivers include a fairly prosperous Earth economy; a response to an ecological catastrophe or scarcity of key terrestrial resources; a push to secure new resources and/or create new markets for Earth; or the urge to explore. Longer term, an established settlement is motivated to self-sustain a viable and growing population.

- Needs Analysis – The diversity of needs of various stakeholders must be considered. Governments need strategic advantage in the event of rivalry; scientists and space agencies need unique knowledge that is only found in space; investors and corporations need predictability of and respect for property rights and returns; markets need a space economy that generates net real wealth; and the public needs to have a clear idea of the motivation for a lunar settlement.

- Transportation and Logistics – To support a thriving lunar economy and future supply chains, Earth-moon transport needs to be more accessible. To this end, a critical economic condition is the order(s) of magnitude reduction in launch costs without compromising safety. Falling costs, a strong focus on safety, and increasing capacity are currently on track with programs for the commercial transportation of humans to LEO and cargo to the moon. Over the medium to long term, lunar propellant resupply from ISRU and safe, reliable habitation at the destinations will continue driving costs down and capacities up.
Investment – Public investment would be motivated by national interest, economic development, and public support, whereas private investment would be motivated by legal and institutional certainty, knowable risks, and the expectation of profits. For business cases to close, governments must establish institutional credibility and buy down risk for commerce, including protection of private property rights; the cost of access to space must fall; publicly funded infrastructure must be in place; and, optionally, government can be the first but not the only customer for space products and services. It is likely that potential profits within a <10-year venture capital time horizon will attract increased investment capital, further justifying the public buy-down of risk.

Habitation – Long-term space settlements are both socioeconomic and physical constructs, and thus are subject to complex dynamics that are not familiar to space programs. To support a thriving economy, settlements need to be safe, comfortable, and interesting so as to attract potential residents and workers. Long-term investment in human-centered settlements with sophisticated socio-technical designs will support a positive feedback loop between happiness and productivity, which are conducive to economic viability.

Resource Extraction – The costs associated with the extraction and processing of water, volatiles, and minerals on the lunar surface currently make it difficult to justify as a standalone business case. Governments should focus on investment in large-scale mining of water ice and regolith, thereby reducing transport costs through fuel and launch/landing infrastructure, with facilities transitioning to the private sector when the business case becomes viable. Robotic mining, which is now available on Earth, may be part of business cases for mining on the moon. Additionally, regulatory frameworks regarding ISRU must be established to provide private entities with clear guidelines on resource ownership and use.

Industrial Development – ISRU, transportation infrastructure, habitat construction, and tourism are likely to be synergistic industries that would benefit from simultaneous development. Humans on-site add value to industrial processes, while robotics, telerobotics, and artificial intelligence could augment scarce labor, reduce risks and ensure safety for tourists. Efficient manufacturing for space and for Earth would require orders of magnitude reductions in transport costs, an ISRU-based value chain, and re-use or adaptation of commercial off-the-shelf (COTS) technologies, where possible. There are first mover advantages with respect to locations that can support long-term organic growth.

Products, Services and Other Outcomes – Once the preceding economic conditions are met, free markets will discover product and service opportunities, possibly among the listed technology gaps. As we cannot yet predict what these will be, infrastructure planning should allow, support, and encourage markets to experiment with a diverse variety of “people” and “value-adding” activities. Some examples included exploration data, resource mapping, lunar science infeasible from Earth, tourism, products valued on the moon and on Earth, and leasing of habitable space to a variety of users. In the long term, and with critical mass, more ambitious business cases might close, such as support for mega-engineering projects in cislunar space, lunar sport and entertainment, and permanent lunar settlement.

Sustainability and Other Conditions – A key condition for long-term sustainability is that all supporting infrastructure for humans and robots will have to be maintained. For this to happen, stakeholders must have the economic motivation to do so. Thus, in the short and medium term, the settlement must provide value back to the public or private Earth sponsors. In the longer term, the settlement must be on a path of ever-increasing economic independence, aspiring towards a self-feeding economy characterized by organic growth and supported at most by small, flat public funding. Further factors to promote sustainability are a stewardship mindset, generational learning, reducing wealth gaps and engaging populations, and channeling the human instinct to explore towards peaceful outcomes.

INFORMATION NEEDED TO ADVANCE TECHNOLOGY AND ECONOMIC CONDITIONS

A thriving economy, including the conditions listed above, is predicated on good information flow. In order to advance sustainable, long-term economic conditions on the moon and address current technology gaps, stakeholders need access to reliable and accessible information, to understand where there is potential for technology development or business opportunity, as well as policy issues regarding consensus rules of engagement for all actors. There are several key information areas that require greater data collection or definition:

Understanding Availability, Mining, and Applications of Lunar Resources – Development of ISRU technology is useless without knowledge about the types of resources on the moon and their distribution, as well as how to work with the materials and their applications. There is an opportunity for lunar missions to focus on lunar materials and products that may be in short supply on Earth in the future, or cannot be produced easily elsewhere, which could have a strong return on investment.

Market Development and Customer Discovery – A key aspect of establishing a lunar economy is discovering viable markets and customers. Supply and demand need to be aligned, as well as a determination of the cost of products and services, and an understanding of potential profit and customer needs. Revealing what customers want will be a difficult task, but it is vital to a lunar economy. Market development and customer discovery could be conducted by a commercial partner with expertise, as was the case with NASA’s LEO commercialization plan [4].

Innovative Business Cases – Business cases for the moon remain a major open question. Workshop attendees believe that there will need to be incentives for businesses to go to the moon. Businesses could start by identifying low-hanging fruit in business ideas, but they must also plan for the long term. New figures of merit will need to be developed to assess the strength of proposed business plans. Although this is a difficult challenge, we can leverage the management lessons learned from New Space companies that are advancing the state of the art.

Consensus Rules of Engagement – NASA’s Artemis Accords are a good start to consensus rules of engagement, and more work will need to be done to ensure safe exploration of the moon [5]. With governments around the world and commercial partners planning to go to the moon, consensus will need to be built on numerous topics, including intellectual property, property rights, collaborative environments, resource sharing, and standards, to name a few.

Marketing – The space community needs to improve its marketing, both to companies and to the public. Companies that have not previously been involved with space exploration should be tapped and small businesses should be encouraged. Space explorers need to shift the public perspective of space toward understanding its potential to solve the most pressing issues of humanity’s future, including growing energy needs. Space needs to benefit not just the wealthy and the privileged, but everyone on Earth—and this will only be achieved when we tap into the full spectrum of talent, including groups that have typically not been involved.

Technology Development and Scientific Research – The technology gaps listed previously require significant scientific information gathering. These areas include, but are not limited to, greater knowledge of long-term effects of microgravity on the body, food production in micro- or low-gravity environments, life support systems, effects of long-term isolation on human behavior, solar power distribution, performance of hardware and materials at extremely low temperatures, and developing manufacturing processes for micro- and low gravity. This needs to be supported by significant investment in scientific research. In preparing the National Academies’ next decadal survey on Life and Physical Sciences Research in Space, the alignment of proposed areas of research with the goals of a long-term lunar settlement could be considered as an additional figure of merit when assessing what research to make the national priority [6].
Strategic Planning – NASA and international partners need to continue strong strategic planning for lunar exploration, including technology roadmaps such as the 2020 NASA Technology Taxonomy to carefully articulate and map capability needs, design reference architectures, and detailed plans for core technologies like communication and power distribution [7].

Delineation of Relationships – It is vital for the relationships of all lunar actors (including government, commercial, and international partners) to be defined. These delineations should include plans for commercialization, sustained levels of funding, and further development of relationships with international partners.

THE ROLE OF NASA AND ITS INTERNATIONAL PARTNER AGENCIES

In moving from initial landing and exploration to a sustained lunar settlement, the role of NASA and its partner agencies must shift. The current model for government-industry partnerships, with the government acting as a customer to acquire needed capabilities, cannot be sustained long term. As NASA refocuses on its long-term exploration efforts for Mars after establishing lunar operations, private industry must take up new roles to deliver increased capability at lower costs; however, as highlighted above, there are major challenges for private industry to develop viable business cases for lunar-based operations at present. These include the significant investment required to gather information about lunar resources, a lack of customers or target market, and no clear national and international legal framework within which to operate. Consequently, in addition to their role in establishing early economic conditions for a lunar settlement and acting as an inaugural customer, NASA and its partner agencies should focus on the following steps to pave the way for private industry investment:

Geological and Environmental Information – Companies face significant information gaps when considering business cases for lunar development. NASA and other government agencies should position themselves to generate and make publicly available data that can reduce the burden of risk for businesses looking to operate on the moon. A key information area already highlighted is that of lunar resources. As ISRU emerges as a key area of interest for commercial development on the lunar surface, significant capital investments are required for initial surveying operations. Rather than placing the burden on a single corporate entity, NASA should organize an effort to gather widespread and comprehensive geological and environmental information for the lunar surface. As well as providing knowledge about the availability of local resources, this information will inform the development of equipment and hardware. This will help companies select sites for further, privately-funded study and development.

Regulatory and Legal Standards – NASA should encourage the prompt development of clear regulatory and legal standards for companies working on the moon, including robust engineering standards for hardware and issues surrounding property rights. Efforts should also be made to ensure the protection of space businesses’ intellectual property, while still encouraging information sharing in this early stage of economic development. Existing legal frameworks for operating in non-sovereign environments – such as in the Arctic and Antarctic – can be used to advise both national laws and international agreements to facilitate this process.

Public Sector Funding and Investment – Government contracts are going to remain a key source of revenue for lunar companies for the foreseeable future. NASA and other space agencies should provide long-term direction for the usage of the moon, along with long-term contracts for the private sector beyond just launches and landings. This could take the form of large-scale scientific projects, such as a lunar telescope, or a government-funded survey effort that contracts with private entities. In the future, additional government agencies can take over some of these responsibilities, with the United States Geological Survey or a similar entity taking over the role for collating survey data, for example

Education and Outreach – Lunar companies require a trained and motivated workforce in order to develop the innovative business strategies and technologies required for lunar settlement. NASA is preeminently placed to support and encourage the professionals of the future in both STEM and other relevant fields. NASA’s Office of STEM Engagement and other outreach efforts should be viewed as investments in developing the skills needed for both the public and private lunar sectors and funded accordingly. Given the large amount of scientific and technical knowledge needed to address key technology gaps, NASA should also continue to invest heavily in academic and research grants.

ENGAGEMENT OF NON-AEROSPACE INDUSTRY AND GOVERNMENT PARTNERS

Government-industry partnerships have always been at the core of the United States space program and will be essential for building a sustained lunar settlement. However, given the diversity of expertise and capability that will be required for a long-term lunar settlement, these partnerships must become multidimensional, and industries outside of the traditional aerospace partners should be engaged. Additionally, NASA’s Plan for Sustained Lunar Exploration and Development highlighted that the success of a sustained and vibrant lunar settlement would require not only the participation of NASA’s commercial partners and international partner agencies, but also that of the wider U.S. government. It is crucial to identify key industry partners and government agencies outside of NASA that should be consulted, to address information gaps and ensure long-term economic viability, as well as decrease development times for any required technology. Three examples of non-traditional industry engagement have been highlighted below to show the potential for addressing key technology gaps. A follow-on table gives a comprehensive list of potential non-space industry actors to engage for long-term lunar settlement. While ’short term’ and ‘long term’ were not explicitly defined during the workshop, for the purposes of this paper we are defining short term as the next 10 years, and long term as the next 50 years.

Healthcare, Agriculture, and Food Processing – The health and well-being of lunar residents will be a crucial contributing factor to the success of a long-term settlement. Healthcare professionals such as doctors, nurses, physical therapists, and those who deal with emergency environments, such as emergency medical technicians, will provide great insight on emergency preparedness and the overall health of the astronauts. In addition to healthcare, astronauts will need other essentials such as food, water, and air. Consultation with the agricultural industry will be crucial for achieving successful crop harvesting on the moon, and thus ensuring less reliance on food being shipped from Earth. Other food-related industries such as food safety, packaging, and manufacturing should also be consulted. Expertise from water and waste management industries may provide insight for recycling and cleaning water and waste, and thus for the sustainability and sanitation of the settlement.

Utilities – Power and communications, are critical utilities required for a long-term, safe lunar settlement. Insights into power distribution could come from the solar or nuclear energy industries, both promising areas for energy harvesting. Power distribution in space on the scale of a large lunar settlement has never before been attempted, so engagement with power distribution companies will be vital. Likewise, communication networks on this scale will benefit from the expertise of existing telecommunications companies.

Mining and Construction – As has been previously stated, ISRU is a key technology for sustained lunar settlement. The mining industry on Earth has a wealth of knowledge to provide in the areas of autonomous and safe resource extraction and processing. Given the hazardous, high-risk environment of the lunar surface, expertise from similarly hazardous industries here on Earth, such as off-shore and ice-drilling companies, may provide useful insight into remote operations in hostile environments, safety regulations, and hardware needs. Since much of the lunar resources mined from the surface will be utilized on-site for landing pads and building infrastructure, best practices of the Earth construction and excavation industry should be utilized for safe and efficient construction on the moon.
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A sustainable geostationary space environment requires new norms of behavior

Thomas G. Roberts¹,²,∗ and Carson Bullock²

Edited by Robert Tomos Johanson and Anthony Tabet

HIGHLIGHTS

• The absence of norms of behavior in space poses a threat to peaceful satellite operations.
• Established space actors are resisting the adoption of new norms.
• Historical satellite behavior can inform new norms such as the establishment of a minimum approach distance in the geostationary belt, which can contribute to the identification and stigmatization of highly abnormal behaviors.

Modern life is increasingly dependent on space technologies such as satellite communication, positioning, and remote sensing, but the political system that has enabled these advances remains fragile. In this essay, we highlight normative contestation—disagreements between space stakeholders in how operators should be expected to behave—in the geosynchronous orbital regime (GEO) as a threat to a secure and sustainable space domain. This conflict stems primarily from the interactions between limited resources (e.g. physical space, electromagnetic spectrum assignments) and the emphasis on maintaining total state sovereignty and independence of policy in the international arena. To preserve the peaceful use of the GEO regime, space actors must act soon to establish norms of behavior that dissuade maneuvers which place satellites close together on orbit.

Orbital space is becoming crowded. Although operators have a wide field of choices for the trajectory of their Earth-orbiting satellites, not all orbits serve the same mission objectives. Space mission requirements typically determine a satellite's preferred orbital regime. For Earth-observation satellites, low altitudes are preferred to high ones. For communications missions, the geosynchronous orbital regime (GEO) is particularly useful.[1] In GEO, satellites orbit the Earth at the same rate that the Earth rotates around its axis, making them appear nearly stationary in the sky for observers on the ground. Because this special property exists only along one ring around the Earth—the geostationary belt—real estate in GEO is a finite resource. As mega constellations—networks made up of thousands of satellites—begin populating the lowest-altitude orbital regimes over the next decade, GEO, too, is expected to grow more congested.[2][3]

A more congested space environment poses unique challenges in all orbital regimes. In general, more objects in orbit lead to an increased risk of collision for satellites, which in turn contributes to the growing space debris problem in the domain. In low altitude orbits, satellite collisions—including the notable 2009 collision between a U.S. commercial satellite and a retired Russian communications satellite—have already created thousands of pieces of debris that last years in orbit.[4] Although the risk of on-orbit collision is much lower in GEO than other orbital regimes, satellites must still confront the consequences of a more congested space environment. Neighboring satellites in the geostationary belt are getting closer and closer together.

Role of Norms

To mitigate the complications of congestion both in the geostationary belt and other orbital regimes, many players in the space sector advocate for explicit norms of behavior.[5] Norms are often defined as “standards of proper or acceptable behavior [that] establish expectations and clarify misbehavior.”[6] Critically, norms should be distinguished from behaviors that are merely common; regular occurrence is a necessary condition, but it lacks the internalization, routinization, and expectation of adherence that true norms display. Under this definition, most space activities—including close approaches in GEO—are not bound by any universally-accepted norms. Norms should also be differentiated from laws, which are equipped with legally-binding enforcement mechanisms. This distinction is subtle, as norms and laws can be cyclically related; unspoken and internalized norms of behavior can lead to the creation of formal laws, and the existence of formal laws normatively promote certain behaviors over others. Critically, as we have defined them, norms are informal and non-binding, but can still generate consequences when broken. Clearly identifying states that fail to follow norms may discourage other operators.

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from forming cooperative partnerships with them and may also impede negotiations with their suppliers due to concerns about associating with “bad actors.” While internationally recognized space law does exist, space policy experts, including some state delegations to the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS), generally agree that the existing body of law is insufficient to guide operators’ behavior, with much of it having been written forty to fifty years ago.[7] This body of international law principally includes four core agreements with widespread accession: the Outer Space Treaty (1967), the Rescue Agreement (1968), the Liability Convention (1972), and the Registration Convention (1975).[8] These laws lack enforcement power, and moreover, were written in anticipation of future conflict at a time when established norms of behavior had not yet been created, and thus they can be seen as taken less seriously than counterpart laws which are built on a pre-established shared understanding of right and wrong. Since the international legal framework for space conflicts is less evolved than those for the land, air, and sea domains, and because law progresses very slowly on the basis of consensus, any new international treaties will still necessitate the definition of norms of behavior to effectively promote responsible use of outer space.[9]

When, why, and how new norms are created has been the subject of lively academic discussion since the 1990s. According to the pioneering work by Martha Finnemore and Kathryn Sikkink, international norms undergo a three-phase lifecycle: 1) emergence, wherein the norm begins with just a few influential actors; 2) cascade, wherein the norm grows in acceptance until it reaches a critical mass of proponents and become seen as typical behavior; and 3) internalization, wherein, the norm has become so routine as for its adherence to be assumed and it is no longer the subject of any significant contestation.[10] While some literature suggested a natural evolution through these phases over time, more recent works have increasingly characterized norm change as an intentional process brought about by individual stakeholders.[11] Originally developed for application in the field of sociology and behavioral economics, so-called norm entrepreneurs actively encourage the spread of certain norms. This notion of norm entrepreneurship, in turn, led to the conceptualization of norm “antipreneurs” who resist changes to the norm status quo. The antipreneur framework has been explored to describe the failure of norms to reach cascade or internalization, in the contexts of disarmament, international trade, and democratization.[12][13] This theory has gained traction in the outer space domain because states that have enjoyed the greatest presence throughout history—the United States and Russia—have incentives to preserve the status quo because it has been historically shaped by them for their own benefit. For example, while those states with low access to space have recently acted as norm entrepreneurs in international fora by pushing for modifications to space law to promote equal access, more established space actors respond with antipreneurism by emphasizing the sufficiency of existing space law and the unwillingness to support change.[14]

A New Normal in GEO

There is no internationally agreed-upon minimum separation distance between non-cooperating satellites in GEO.[15] Most satellites maintain safe distances of over 200 kilometers from their nearest neighbors in the geostationary belt.[16] Over the past five years, however, some satellites have made a pattern of getting much closer to their neighbors—distances on the order of 10 kilometers—prompting other satellite operators to make public comments expressing concern.[17] While occasional, short-lived close approaches are often an unintended side effect of operating in a densely populated orbital regime, an intentional, long-duration close approach with a non-cooperative satellite could be interpreted as nefarious behavior. Satellites that are designed to closely approach other satellites could be used for on-orbit visual inspection, receiving another satellite’s communications, or more seriously, as part of an attack designed to disrupt, degrade, or destroy a target.[18]

To take full advantage of the geosynchronous orbital regime, satellites must use station-keeping maneuvers—periodic trajectory adjustments performed by onboard engines—to maintain their positions in the geostationary belt. When a satellite fails to station-keep—either by its operator’s choice or when it reaches the end of its operational life and has expended all of its onboard propellant—its orbital period falls out of sync with the Earth’s rotation due to a combination of external

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**Figure 1**: The geostationary belt. As of January 1, 2020, the U.S. Space Command’s Combined Space Operations Center (CSpOC) database contains the orbital elements for nearly 800 satellites in GEO. The black points represent satellites launched within the past five years. Data Source: U.S. Space Command Combined Space Operations Center / Space-Track.org.
forces from the Moon and Sun, and it appears to slowly drift in the sky for observers on the ground.[19] The same onboard propulsion system that is used to station-keep, however, can also be used to efficiently reposition a satellite from one longitude on the geostationary belt to another.

Unlike other orbital regimes, satellite positions in GEO are regulated by the International Telecommunications Union (ITU), a specialized agency of the United Nations. Charged with preventing harmful interference in the radio-frequency spectrum, the ITU allocates satellite licenses to member states. A geostationary satellite license from the ITU grants the right to communicate in select bands of radio frequencies from specific positions in the geostationary belt, which they can then apportion to individual operators.[20] Without the ITU's regulatory framework, GEO satellites might attempt to communicate with their ground stations over the same frequencies from similar positions in space as their neighbors, confusing receivers on the ground, and jeopardizing the satellites' missions. Due to the geometry of the geostationary belt, orbital positions can be measured in degrees corresponding to the longitude of the point directly below on the Earth's equator. The ITU licensing system also assigns satellites to orbital slots, or small sectors of the geostationary belt, generally about 0.1 or 75 km wide.[21] A GEO satellite at 78.5W, for example, appears directly overhead for observers in Quito, Ecuador. At an altitude of almost 36,000 km, satellites in GEO can observe approximately one third of the Earth's surface, so a satellite at 78.5W is also well-positioned to serve the United States and Canada. Although the ITU frequency licenses only hold for their corresponding orbital slots, satellite operators often choose to maneuver and operate in other parts of the geostationary belt not covered by their original ITU license.[16] In those cases, operators may choose to take over an existing license held by the same ITU member state, not communicate with ground stations while in the new orbital position, or disregard the standards put in place by the ITU.

Although many satellites operate at one longitude for many years, others reposition themselves as their mission requirements change over time. Operators are not required to report satellite maneuvers. So, while some satellite operators publicly declare their plans to reposition their satellites, either through press releases, public filings, or by maintaining an online maneuver schedule, others do not.[22][23][24]

In 2015, a Russian satellite known as both Luch and Olymp-K maneuvered from 96.4E to 17.9W and positioned itself between two Intelsat satellites, getting as close as 10 km to both satellites June and September of that year.[16] Intelsat—a U.S. commercial satellite operator with more than 60 satellites in GEO—quickly expressed concern about the incident. In an interview with SpaceNews in October 2015, after Luch had maneuvered to another location, a senior Intelsat executive called Luch’s behavior "not normal" and "irresponsible," a rare public rebuke of a foreign satellite operator's on-orbit activities.[25] Although there are mechanisms in place for international satellite operators to communicate with one another through the U.S. Department of Defense, which manages a public database of space objects called Space-Track, the Russian Ministry of Defense did not respond to Intelsat's messages, nor are there any existing norms or international laws that might compel it to do so.

Three years later, in September 2018, France accused Russia of using Luch to spy on a military satellite jointly operated by France and Italy.[26] In a public address, the French Minister of the Armed Forces Florence Parly said that Luch "got so close that we might have imagined it was trying to intercept our communications."[27] An analysis of the public space object catalog shows that Luch approached the French satellite in October 2017, almost a year prior to the defense minister’s remarks. Despite the concern from France, the Russian satellite was actually much closer to other neighbors at the time, including Pakistan's Paksat 1R and Russia's own Raduga 4 satellite 5 km and 10 km away respectively. Pakistan has made no public statements about Luch's behavior on orbit.

Since its launch in September 2014, Luch has occupied a wide stretch of the geostationary belt, from 96.4E to 23.6W and seventeen more positions in between.[16] When compared with other GEO satellites in the U.S. Space Command's Combined Space Operations Center (CSpOC) space object catalog, Luch's movements are unprecedented.

Although the CSpOC catalog contains more than 45,000 space objects, it does not include the orbital elements for a small number of military satellites from the U.S. and its allies. According to data from the International Scientific Optical Network, a space surveillance network...
managed by the Russian Academy of Sciences, several U.S. satellites—USA 253, 254, 270, and 271—have performed close approach maneuvers with non-cooperative satellites from Russia, China, Pakistan, and Nigeria at distances near 10 km. [28] The recently declassified Geosynchronous Space Situational Awareness Program (GSSAP) likely uses pairs of satellites in near-geostationary orbits to inspect satellites from above and below as opposed to occupying a nearby slot in the geostationary belt itself.

Mechanisms for a New Norm of Behavior for GEO Operations

What has been done to promote or prevent norms of behavior in the space domain, and where do these contemporary efforts stand? The United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) publishes voluntary guidelines on long-term sustainability via a working group of its Scientific and Technical Subcommittee. The process began in 2010, and the guidelines were finalized and fully adopted in June 2019. [29] Historically, these guidelines have been informed by recommendations from other international organizations, such as the ITU and the Interagency Debris Coordination Committee (IADC), a collection of national civil space agencies dedicated to mitigating the creation of space debris. Typically, COPUOS, despite it being the primary forum for international norm-setting, continues to defer to national implementation strategies, and each session gives state delegations ample time to discuss their own national contexts. While this practice allows states that routinely follow existing voluntary guidelines to lead by example, it unfortunately also leaves room for states to remain lax in their implementation.

As a salient example, we may consider the norm surrounding post-mission deorbiting for lower-altitude satellites. The 2019 update to COPUOS' recommendations includes the phrase "the post-mission lifetime of a satellite in orbit should not exceed 25 years." This 25-year rule came directly from a 2007 recommendation by the IADC, which in turn was based on a guideline from a set of internal NASA standard practices published in 2001. [30] However, the same NASA document allows for a number of possible exceptions from this rule via storage orbits, exemplifying the push and pull between international organizations that take cues, at times aggressively, from national regulations that may in practice be more lax when applied in those national contexts.

How might a voluntary guideline on the minimum close approach distance affect satellite behavior in the geostationary belt? Suppose the Committee’s member states agreed on a close approach distance of 10 km in GEO—effectively forbidding the maneuvering behavior of Luch and the GSSAP satellites that some operators have deemed "too close" to other neighbors. An analysis of the last five years of satellite maneuvering activity in the geostationary belt suggests that the vast majority of satellites—approximately 96 percent— already adhere to this norm on a daily basis. Only a small number of satellites would need to adjust their behavior to no longer violate the new norm. However, the act of recommending a close-approach distance remains important because it changes the norm status quo by making explicit a previously implicit assumption by the majority of space operators that they should not approach other satellites without permission. Setting a low threshold, such as 2 km (which would require fewer than 1 percent of satellites to change their regular behavior), may not encourage any operator to critically examine their behavior, while setting a high threshold, such as 25 km (which would affect more than 10 times as many satellites), may make compliance needlessly burdensome. As the geostationary belt becomes more congested, space system engineers have incentives to design satellites that can safely operate in closer proximity to one another, rendering a specific close approach threshold obsolete. A voluntary guideline is best positioned for success when it is both clearly achievable and negotiable over time, leaving enough rule-breakers to be effectively named, shamed, and catalogued by good-faith actors.

To complement the formal process at COPUOS, Transparency and Confidence-Building Measures (TCBMs) represent a strong platform for promoting both terrestrial and space cooperation by facilitating predictable processes. The Secure World Foundation and Open Lunar Foundation have held workshops, most recently in December 2019, on “rationales behind norms and norm creation and adherence, avenues for norm development, and the life cycle of norms.” [7] Participants were encouraged to propose their own space sustainability recommendations. Workshops like these can be part of a wider lineage of diplomacy that lies between formal channels and grassroots norm change approaches, which have a history of success in measures of confidence-building. [31]

Regardless of the forum in which satellites operators develop norms of behavior in the geostationary belt—either in response to continued close approach behavior by a small handful of actors or in an attempt to anticipate and prevent it—the changing space environment demands that space actors act soon to preserve the peaceful, sustainable use of the regime for decades to come.

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References

AN ADVANCE MARKET COMMITMENT PROGRAM FOR LOW EARTH ORBIT ACTIVE DEBRIS REMOVAL

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A. Introduction and Summary Findings

Humanity’s spaceflight activities over the last six decades have left Earth orbit littered with tens of thousands of objects large enough to track, and hundreds of thousands more too small to track, but large enough to disable a satellite. Consensus exists within the orbital debris community that Active Debris Removal (ADR) from Low Earth Orbit (LEO) is necessary to stabilize the orbital debris population, even with strong compliance with Post-Mission Disposal (PMD) guidelines for current and future missions [1]. Without such action, the catastrophic fragmentation of large debris objects threatens the safety of LEO and would dramatically increase the cost of eventual remediation [2].

Unfortunately, U.S. progress towards development of ADR capabilities has been limited, slow, and largely theoretical. When transitioning from this status-quo to an operational ADR capability, private sector development/commercialization of ADR technology is preferable to government-conducted ADR for several reasons. Commercializing ADR would lower costs and increase efficiency and

Figure 1: Visualization of Tracked Low Earth Orbit Resident Space Objects

Source: produced by the authors using Analytical Graphics, Inc.’s STK Software
scalability, weaken the perception of ADR as a dual-use technology for counterspace activities, and help develop the space industrial base. At the same time, commercial ADR capability development is limited by lack of a clear market, low and uncertain willingness to pay among governments and existing operators, real but solvable technical challenges, and unresolved policy issues.

The Advance Market Commitment (AMC) concept, pioneered for vaccines by the global health community, offers a valuable public policy lever that should be applied to the ADR problem to help speed up the development of private sector ADR capabilities and encourage deployment at socially efficient, rather than laissez-faire market clearing levels. The AMC concept helps pull technology development forward by providing a binding commitment to purchase a certain number of units of a product at a premium price in return for a guarantee by the seller(s) to offer some additional subsequent quantity at near marginal cost. Through this structure, the AMC tackles two problems critical for ADR: it induces market entry by firms who might otherwise not consider a potential market sufficiently lucrative to justify Research and Development (R&D) investment, and it avoids the deadweight loss associated with firms exerting market power to extract profits above marginal cost.

The three key findings of this paper are:

1) There is a need to develop ADR technology to ensure sustainable access to space for current and future spacecraft. The U.S. government should enact “pull” policies to advance ADR technology, commercialize that technology, and develop a market around ADR.

2) An AMC should be the preferred model for that policy, modeled on successful work for vaccine AMCs by the global health community. The AMC should feature 1) a binding government funding commitment, 2) technical requirements for ADR product eligibility, 3) an independent adjudication committee to make program-related determinations, and 4) a funding allocation model sufficient to induce market entry by two to three firms. Further study is required to understand the unique nuances of an ADR AMC and develop an implementable proposal.

3) An AMC ADR is consistent with the U.S. National Space Policy and Space Policy Directive-3.

B. Background/Literature Review

The space debris problem: Humans derive significant benefits from space-based services including Earth observation, satellite communications, and position, navigation, and timing for civil, national security, and commercial purposes. The satellites that deliver these services and their attendant benefits rely on the ability to safely operate within Earth orbit. Within both LEO and Geosynchronous Earth Orbit (GEO), orbital debris poses a real and growing threat to the safety of operating spacecraft, and the potential for further fragmentation events that would generate even more collisions.

1 While this concern is raised frequently, an in-depth report looking into this issue found that experts believe that easy attribution renders the covert use of ADR spacecraft as antisatellite weapons unlikely. [53].
Guidelines exist to prevent the generation of further debris. While compliance with the relatively modest 25 year rule for PMD is slowly improving (see Figure 2), it remains significantly worse for satellites (<40%) and rocket bodies (<65%) in non-naturally compliant orbits [9]. Meanwhile, even with lower historical launch rates and 90% PMD compliance, modeling by the NASA Orbital Debris Program Office demonstrated yearly ADR of approximately five objects would be required to stabilize the population [10]. In a more realistic scenario where the number of new objects on orbit continues to grow rapidly and starting from today’s more congested baseline, significantly more ADR will be needed. The increase in tracked objects is visible in the top graph of Figure 2.

The current status of ADR technology: Government R&D incentives can either subsidize research inputs (known as “push” policies), or, like the AMC concept, provide rewards for developed products or other research outputs (known as a “pull” policy). Both types of policies are complementary, and government-funded initial technology push work has helped mature much of the technology needed for both on-orbit satellite servicing and ADR.

Numerous ADR technologies have been proposed including tethers, tugs, drag augmentation devices, and lasers with different applicability to different orbital regimes, operational concepts, and debris object sizes [11,12]. Liou and co-authors have proposed and validated a simple metric based on probability of collision and object mass [10,13,14]. Subsequent efforts have sought to develop more sophisticated indices to quantify the orbital risk or environmental criticality of debris and active spacecraft [15–20]. McKnight et al. argue that large derelict objects in congested high LEO orbits should be prioritized for ADR due to the high probabilities and consequences of an inevitable collision, and the significantly increased cost and difficulty of post-fragmentation remediation [2].

Various ideas for ADR “pull” programs have been proposed including prizes [21] and debris bounties [22]. There have also been proposals, such as orbital use-fees [23], that would increase costs for debris generation and implicitly incentivize ADR. For instance, the Federal Communications Commission (FCC) proposed a performance bond for successful PMD as part of its on-going space debris rule-making, although this proposal has been sharply criticized by industry [24].
Rao has conducted the most extensive theoretical exploration of the economics of space traffic control to date [25]. Assuming open access, his model assumes operators will launch until the profit from a new satellite becomes zero. Under such conditions, he demonstrates that ADR technology will only reduce aggregate collision risk if debris is actually removed and satellite owners pay for removal. Otherwise, government or philanthropy funded ADR will simply induce an increase in new spacecraft until excess return (compared to the next-best investment option) is equal to the private cost of collision risk. Furthermore, he demonstrates that operator purchases of ADR will be based on their own privately optimal ADR quantity rather than a pareto-optimal level of ADR. Muller et al. have also performed theoretical work to quantify operator willingness to pay for ADR [26].

Only limited work has been performed examining the sensitivity of start date on ADR efficacy. Liou found approximately seven additional catastrophic collisions (an increase from 25 to 32) and 2,000 more debris objects would result from starting ADR in 2060 rather than 2020 [10]. In practice, the actual difference is likely to be significantly greater than reported in this study, as PMD rates continue to be well below those used in the study and launch volumes have expanded considerably compared to the study’s assumptions. An ESA webpage cites internal ESA studies showing that waiting until 2060 would reduce the benefit of ADR by 25% versus starting in 2020 [27]. McKnight has argued for more than a decade that starting immediately is necessary to avoid a significantly higher cost for eventual ADR, both for direct remediation and due to termination of active missions in the additional intervening time period [28,29].

There have been many theoretical studies of ADR technology, and a limited number of relevant flight missions. The Surrey Space Centre and partners demonstrated capture of a target object via a net and a harpoon on the RemoveDEBRIS mission [30]. ESA has commissioned an active debris removal mission from ClearSpace, a space startup spun-off from Ecole Polytechnique Fédérale de Lausanne [31]. The mission will remove a 100 kg payload adapter left by a previous ESA mission [31]. NASA’s OSAM-1 mission (formerly Restore-L) passed Key Decision Point-C earlier this year and will demonstrate satellite servicing and on-orbit assembly, including many technologies required for ADR [32]. DARPA’s Robotic Servicing of Geosynchronous Satellites (RSGS) project will demonstrate servicing in GEO using a Northrop Grumman Mission Extension Vehicle (MEV) as the bus, and is scheduled for launch in 2023 [33,34].

Among commercial actors, Astroscale is developing a commercial ADR service, and has received a contract from the Japan Aerospace Exploration Agency (JAXA) for the Phase I of JAXA’s first debris removal project [35]. It plans to launch a self-funded demonstration mission soon, potentially by the end of this year [36]. Northrop Grumman’s Mission Extension Vehicle (MEV) demonstrated commercial life extension service at GEO, including transferring a satellite to GEO graveyard for testing before returning to its nominal orbital slot [37,38]. Two MEVs are currently in orbit.
The AMC concept: There are many possible variations in potential AMC design. Under the AMC concept recommended here (as seen in Figure 3), a government or other entity offers a binding commitment to pay a per-unit price or subsidy to sellers of a good or service that meets certain quality standards in return for a commitment by that seller to, for some time period, offer to maintain capability to supply some minimum quantity of the product and to price additional units above the AMC quantity at a lower price near to its marginal cost. AMCs incentivize the private sector to develop and commercialize solutions for the chosen problem, but subsidize and front-load returns to the seller to ensure that the product is then available at close to its marginal cost of production at levels closer to socially market-clearing quantities. This last quality is what makes AMCs well suited to problems where the desired outcome is known but the benefits of a product are broadly diffused and there is low (but non-zero) willingness to pay within the targeted customer base.

Kremer and Glennerster argue that for vaccines in low income countries, AMCs outperform alternatives such as patent extensions, best-entry tournaments, or purchasing adjacent

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2 This is known as a supply commitment. In the monopoly case, improvements in the theoretical efficiency of the AMC can be obtained by only offering the subsidy to firms if they produce at least the specified level of output, a forcing contract. This paper recommends supply commitments rather than forcing contracts due to various practical considerations that become challenging under the latter approach [44].
products at premium prices, providing better access, quality incentives, prices to consumers, and return per government dollar [39]. These same arguments hold for an ADR AMC.

**The Pneumococcal Conjugate Vaccine AMC:** The AMC concept was first developed by the global health community in the context of vaccines. Drawing on a variety of earlier discussions, the idea was first presented at length in [39], and developed into a practical proposal by [40]. A pilot program testing the AMC concept for the Pneumococcal Conjugate Vaccine (PCV) was funded in 2007 by a group of five countries and the Bill and Melinda Gates Foundation [8]. The effort launched in 2009 under the administration of GAVI, a Non-Governmental Organization (NGO) that focuses on vaccination in poor countries [8]. The PCV AMC is highly cost-effective, with higher population coverage in participating countries, and with more rapid adoption and better vaccine supply availability than a comparable virus for which an AMC did not occur [8].

**C. Analysis and AMC Design: Applying the AMC Model to ADR**

This section provides a high-level set of recommendations concerning the design of a U.S. government AMC for ADR focused on removal of large debris objects from LEO. Further development from these initial findings by a committee of experts would be necessary to develop an implementable AMC. This paper refrains from specifying a specific agency to manage the AMC, due to ongoing debates regarding where to place responsibility for civil space situational awareness and space traffic management within the U.S. government [41,42]. Responsibility for promoting the development of commercial debris remediation technology would be highly synergistic for whatever agency is given the civil SSA/STM mandate. Maclay and McKnight coin the term “Space Operations Assurance” to describe such a framework where space environment management (consisting of debris mitigation and remediation) and space traffic management are combined to ensure safety of flight, building on a bedrock of high quality actionable SSA information and emphasize the need for such an integrated perspective [43]. Eventually, if ADR were broadly available and affordable, the FCC might conceivably issue a regulatory requirement for owner-operator contracted ADR of failed satellites, but it would be outside its mission to run an ADR AMC to reach that scenario. Regardless of which civil agency is given the relevant mission, it is important that the AMC should be funded and overseen by a civil rather than military organization (e.g. the Defense Advanced Research Projects Agency), to help address dual-use concerns.

**Recommendation #1 The AMC should be legally binding for the U.S. government and participants:** In order for firms to invest R&D in response to an AMC, they must find the offer to be credible, as they will experience a loss if the funder reneges. Consistent with the recommendations from the literature [44], the ADR AMC should be legally binding, with rules specified in advance for eligibility and pricing, with an Independent Adjudication Committee (IAC) (discussed more in the section below) insulated from political pressure. There should be a binding contract clause obligating the government to fulfill the AMC. If this cannot be done due to

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3 It would also be possible to design an AMC for smaller lethal non-trackable objects, a more technologically distant application with less technological overlap with satellite servicing technology. This would be a more ambitious and uncertain area with several additional concerns. These include the international legal status of unattributed debris, uncertainty whether private market demand exists or would ever exist for removal of lethal non-trackable objects from various orbits, and the cost effectiveness of small debris remediation.
annual budgeting or insufficient political will, the contract should provide for payment of closeout costs sufficient to make participating firms whole if the government does cancel the AMC.

**Recommendation #2 ADR products should be required to meet basic technical requirements for eligibility:** In order for firms to qualify for the AMC, Kremer and Glennerster recommend that the offering organization define clear standards (ideally as objective as possible) in advance for safety, efficacy, and usability that a product will need to meet to qualify for the AMC [39]. This section describes what those standards might look like for an ADR AMC. Defining these standards should be done in a technology neutral way that avoids specifying the specific ADR technology.

**Safety:** No U.S. agency has clear oversight authority for on-orbit activities other than remote sensing or communication. The Trump White House designated the Department of Commerce’s Office of Space Commerce as the intended agency to authorize and supervise ADR and other missions that fall into this gap, but Congress did not grant it authority to do so and the Biden’s administration did not granted it authority to do so. Requiring mission licensing and using licensing as a safety criterion is a reasonable standard. The AMC offering entity could also require compliance with all relevant CONFERS standards. Naturally, Outer Space Treaty compliance, including securing launching state permission for ADR of any non-U.S. objects, is implicit in mission authorization.

**Efficacy:** Kremer and Glennerster recommend that efficacy standards be flexible enough to encourage promising leads but not so weak as to lead to an unusable product. In the ADR context, the relevant metric is reduction in collision risk. Liou and Johnson propose a reasonable strategy of quantifying risk $R$ (and this risk reduction from ADR) as the product of probability of collision, $P_c$, and mass, $m$. [10,13]

$$R = P_c m$$

As described in the background section, more sophisticated techniques also exist. An expert group would need to select a mechanism and define an objective procedure concerning how to calculate the probability of collision on a per-object basis and adequately capture the effects of derivative collisions. $R$ values could be used by both buyers and sellers to quantify mission concept efficacy (and thus price) and to prioritize objects for removal.

**Usability:** Many different proposed ADR techniques exist, with applicability to different object sizes, altitude regimes, and object properties. One challenge for any kind of pull policy will be to ensure that the incentivized projects actually respond to the desired user need.

One key advantage of the AMC design is that it can be used to impose a market acceptability test on providers through the use of co-payments: the provider must find customers willing to procure ADR services at the subsidized rate to receive the subsidy. This encourages operators to offer ADR services responsive to the altitudes, spacecraft designs, and masses of potential customers. Further work should be conducted to engage with stakeholders to better understand their usability concerns and how these concerns should influence potential AMC design.

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4 The Consortium for Execution of Rendezvous and Servicing Operations (CONFERS), is an industry-led organization for the development of best practices and standards for rendezvous and proximity operations and on-orbit servicing.
As demonstrated in Rao’s work, incentives regarding which objects to prioritize and how many to remove differ between governments and private actors. A holistically-minded U.S. government buyer will presumably be motivated by maximizing total welfare through socially efficient target selection and ADR quantity. In contrast, private actors are more likely to base decision-making on the risk reduction to their own assets. There is likely to be significant overlap in the technology to serve these two goals, but differing target selection and (potentially) product design. The best way to address this split may be through a hybrid market acceptability test, with a set of government-funded missions targeted at best reducing overall debris risk in LEO and a portion of the AMC subsidy pool reserved for missions procured by commercial operators. Such a structure would ensure responsiveness to both constituencies, and increase the likelihood that commercially available ADR products are available to and purchased by both governments and commercial operators even after the end of the AMC period.

**Recommendation #3 Program determinations should be overseen by an independent adjudication committee:** Because the incentives of the funder are not necessarily aligned with those of participating companies, there is a risk that the funder might use its power to reduce returns for companies once they had funded their R&D or otherwise interfere in decision-making for political or other undesirable reasons. To address these concerns, Kremer and Glennerster recommend the creation of an IAC of technical experts to verify compliance with the technical requirements for eligibility [39]. The IAC would also have the ability to waive technical requirements other than regulatory approval, oversee sales for continued safety and efficacy, and potentially discontinue purchases if safety or efficacy is determined to be worse than at initial approval (subject to clear pre-specified rules and processes). It could waive (but not increase) technical requirements if a promising entry existed that did not quite meet all the AMC technical requirements, and make determinations related to sponsor exit requirements (e.g., if no responsive products are developed over the AMC period, or if there is a change in circumstances that obviates the need for ADR). 5

Kremer and Glennerster further recommend selecting IAC members trusted by the industry participants in the AMC, because their confidence is critical and they have the most to lose should the IAC be influenced by political pressure [39]. The process and IAC assembled for the PCV AMC provide a strong template which could be used for the ADR case. A list of areas of expertise was determined in consultation with stakeholders, and an IAC Selection and Oversight Panel was established to select members and review claims of conflict of interest involving IAC members [45]. The PCV AMC IAC ultimately selected featured an international set of experts from academia, multiple governments, and industry with widespread expertise in the relevant fields.

**Recommendation #4 Determining program pricing will require further study:** Getting pricing right and securing sufficient capital to fund the AMC will be challenging. The pool will

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5 Exit due to non-response would be a graduated process. If after a certain period of time, say 15 years, no responsive product had been submitted, the IAC could announce that in another 5 years the AMC would end unless an eligible product had been approved by that point. AMC cancellation due to elimination of need is less relevant for ADR than in the vaccine case, where a disease might be essentially eliminated without the new vaccine. One potential analogous ADR contingency is if on-orbit assembly capabilities cause the business case to close for on-orbit salvage rather than removal. Kremmer and Glennerster recommend requiring an IAC supermajority and allowing legal challenge for these kinds of cancellations [39].
need to present a credible net present value for two to three entrants. More extensive modeling factoring in probable cost and timeline for development, cost of capital for potential bidders, and marginal cost of missions will be necessary. This modeling should be informed by conversations with existing and potential ADR companies, launch vehicle providers, and government/NGO experts. To date, public work has not been able to credibly price either willingness to pay for ADR, or the cost of providing it. Market leader Astroscale has laid out thinking regarding its value proposition in qualitative form [4]. Yamamoto et al. attempted to model cost of ADR to find the lowest cost architecture, but concluded that their model could not reliably estimate the absolute cost of ADR [46]. Braun et al. use cost estimation relationships to estimate non-recurring research, development, testing, and evaluation (RDT&E), theoretical first unit (TFU), launch costs, and operation costs [47]. They found costs depend heavily on target objects, the number of objects removed per mission, propulsion type, and launch costs. Their estimates range from $8,100 to $34,000 2020 dollars per kg of mass removed, excluding learning curves and RDT&E. They estimated RDT&E costs of approximately $430-$730M 2020 dollars.

There are also considerably differences in how technologically close or far different ADR concepts and companies are from product availability. Optimal AMC incentive structures differ somewhat for technologically close (where the majority of research and development spending has already taken place) versus for more technologically products (where it has not) [44]. Subsidy design is more challenging and expensive for technologically close products due to better private price information among offerors and a need to properly shape the incentive structure to actually increase offeror capacity investment [44]. For technologically distant products, the overall amount of subsidy is important to spur R&D, and there is a need to guard against usability issues which are hard to specify in advance (for which a co-payment requirement provides a possible solution) [44].

**Pricing should be designed to attract two to three suppliers:** Design of an AMC’s subsidy mechanism depends heavily on how many suppliers the program should seek to incentivize to participate. On one hand, more firms lead to more competition and reduce purchase prices in the long term, increase resiliency and capacity, and allow for product differentiation for different niches. On the other, including more suppliers within the AMC dilutes the per firm incentives and increases the subsidy necessary to incentivize entry.

AMC designers can adjust the size of the total subsidy, per-unit subsidy amounts, and the rate at which the subsidy is dispersed over the course of the program. These factors should be set to attract two to three suppliers. Having a single supplier weakens market forces and price pressure after the expiration of the AMC supply commitment period. It also would leave the program vulnerable should a supplier experience a technical or business failure. With at least one company already credibly developing ADR capabilities, securing participation of two to three suppliers should be possible. Having multiplier supplies also allows for the possibility that

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6 During class discussion, a participant asked how the AMC model could accommodate ADR offered as an insurance product rather than a per-mission basis. This could be addressed by price commitments for those premiums.

7 Values were inflated to 2020 dollars using the U.S. Bureau of Labor Statistics Consumer Price Index and rounded to two significant figures.
technological reasons or segmented customer demand may lead to firms developing ADR products targeting different market niches.

Recognizing that companies may develop and field their products at different speeds, the program should be designed to permit later entry by subsequent firms. Mechanisms to ensure this could include limiting any one firm to no more than 60% of the total AMC quantity (either in total or per year), offering higher subsidies for the first several missions by the first three firms, and imposing diversification requirements as part of the basic technical requirements (e.g., ability to launch on multiple launch vehicles, or use of a different launch vehicle than other approved AMC participants). If per-object or risk-reduction based bonuses are included, designers should be aware that there will be implicitly diminishing returns as early missions target the highest reward objects for which they can secure permission and which are technically feasible to remove with their technology. Depending on AMC design, firms may seek to secure large operators as anchor customers and design their AMC offering to be heavily responsive to the needs of those operators, provided they can still meet the technical eligibility requirements for the AMC. Incentivizing responsiveness to operator needs is a valuable market test that helps ensure the development of a self-sufficient market following the end of the AMC.

D. Policy Considerations

An ADR AMC is consistent with current U.S. policy: An ADR AMC aligns with current U.S. space policy [48], both in terms of pursuing ADR as part of efforts to ensure space sustainability, and through preferring the development of commercial rather than government-driven capabilities for achieving the objective while promoting American technological leadership. The current national space policy states that the United States shall “Evaluate and pursue, in coordination with allies and partners, active debris removal as a potential long-term approach to ensure the safety of flight in key orbital regimes” [48]. It also sets a goal to “to facilitate the creation of new global and domestic markets for United States space goods and services, and strengthen and preserve the position of the United States as the global partner of choice for international space commerce.” Space Policy Directive-3 offers similar language [49].

The National Space Policy’s guidelines sets out a tiered approach for government purchase of commercial space capabilities, prioritizing the acquisition of space services and goods from the private sector where possible to “promote a robust domestic commercial space industry and strengthen United States leadership” [48]. These include:

1) Preferring to purchase commercial services that meet U.S. requirements, modifying those services for government requirements if it would be a “cost-effective and timely” approach;
2) Actively exploring the use of “inventive, nontraditional arrangements” for acquiring space goods and services to meet U.S. government requirement; and
3) Developing governmental space systems only “when in the national interest and no suitable or cost-effective United States commercial or, as appropriate, international commercial capability or service is available or could be available in time to meet Government requirements[.]”

Depending on the level of development of ADR technologies when an AMC was implemented, the government purchase would fall into one or more of these first two categories.

The recently released National Orbital Debris Research and Development Plan calls for:
1) The development of remediation technologies for both small and large debris objects;
2) Technologies to repurpose large debris objects; and
3) Models to better assess risk and cost-benefit trade-offs associated with debris remediation and repurposing [50].

The report is less aggressive than this proposal, focusing on a research agenda for the Department of Commerce, Department of Defense, and NASA rather than envisioning commercialization or seeking an operational ADR market promotion effort [50].

**ADR-related policy concerns can be adequately mitigated by an ADR AMC Program:** In 2011, Brian Weeden, one of the world’s leading experts on space sustainability, authored an overview of the legal and policy challenges of ADR [6]. Among the issues he cites are eight highlights:

1. A lack of a legal mechanism to distinguish functioning satellites from debris;
2. Issues with selecting objects for removal (chiefly that there are multiple potential methodologies, and that the highest priority objects are all Russian-owned);
3. That launching states retain ownership of debris objects but the launching state is unknown for some objects;
4. That there is no one authoritative catalog for space objects;
5. That ADR operations potentially increase risks for other space activities;
6. That the dual-use potential of ADR technology could increase tensions and even spark conflict;
7. That close imaging and characterization of debris for an ADR mission might reveal trade-secrets or other proprietary information about the object;
8. And that there are unresolved liability issues for ADR.

While the set of policy issues has not changed much since 2011 (for instance, see [7]), none of these are insurmountable.

Concern 1 (legally distinguishing satellites from debris), 3 (launching state ownership), and 4 (lack of an authoritative SSA catalog) could be addressed by limiting removal to objects that are well-tracked by USSTRATCOM or commercial SSA providers, clearly attributable to a launching state, and for which the launching state is willing to give permission for removal.\(^8\)

The finer points of debris object selection (concern 2) should be defined as part of the basic technical requirements with clarifications provided by the IAC as necessary. The basic safety requirements for AMC eligibility provide a way to mitigate concern 5 (risk to other space objects). The use of commercial ADR capabilities, developed and operated at arms-length from government, helps mitigate concern 6 (dual-use). A commercial company has a profit

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\(^8\) “Well-tracked” and “clearly attributable” are admittedly subjective terms that would need to be defined further as part of the AMC design process, with the IAC handling any disputes or ambiguities. The AMC’s technical requirement for regulatory authorization also provides another implicit backstop against selection of technically or diplomatically problematic targets. Additionally, a requirement for permission from the launching state of the removed object implies international acceptance of responsibility for that object, which is a fairly conservative requirement for attribution that should address most potential ownership-based objections. In correspondence with the authors, Akhil Rao noted that implementation of an orbital-use fee system would incentivize operators in ways that would help address many of these concerns by motivating operators to declare defunct objects as debris and seek removal.
maximizing incentive that encourages it to maintain good relations with potential commercial and government customers internationally, can be more transparent about capabilities and actions than government actor with blended national security and civil concerns, and is potentially subject to overlapping multinational governance and regulatory regimes for the country(ies) where it is based and/or offers service, unlike a sovereign government. This could be even further strengthened by requiring companies to agree to refrain from offering national security services, IP, or technical assistance derived from their ADR technology as a condition of AMC eligibility. However, such a request would make it more challenging for such companies to close their business cases and diversify their customer base, potentially reducing participation in the AMC. Concern 7 could be addressed with another requirement, requiring companies to not disclose or make any non-operational use of IP or other potentially proprietary information derived from imaging or other interaction with a debris object. This could be assured using tools from other contexts that deal with restricted use IP including contractual commitments, internal firewalls/access restrictions, third-party compliance auditing, and through setting appropriate company culture. There are also significant restrictions in U.S. law regarding non-Earth imaging. Further work at the international level would enhance ADR and ADR AMC efficacy but is not a prerequisite.

Concern 8, liability issues of ADR, is the most complex. Clarifying or updating international law will be too slow to be useful for the AMC program. The alternatives are to require operators to shoulder the liability burden (either individually or on a pooled basis), to have the U.S. government agree to some form of indemnification, or a hybrid. The indemnification the U.S. government provides to launch providers could present one such model (see Figure 4) [51]. Operators are required to obtain private insurance up to a maximum probable loss (MPL) amount, with the government then accepting liability up to a certain level, and liability beyond that amount returning to the business. Commercial markets can provide some level of insurance, and the threat of liability up to the MPL incentivizes companies to behave safely, but the government risk assumption reduces overall costs and indemnifies low probability high consequence risk beyond what the commercial market could bear. The extremely low probability but theoretically unlimited risk above this threshold returns to the company. This avoids unlimited direct liability for the U.S. government (although the U.S. still ultimately bears that liability at the international level). At the same time, this remaining risk may be sufficiently remote for launch providers to accept it, even at the cost of potential bankruptcy should it occur, rather than proactively insure against it (which may be impossible at reasonable rates). Another option would be for government to provide indemnification so long as missions follow certain safety standards, or indemnify enough

Figure 4: U.S. Indemnification Regime for FAA-Licensed Launches (FY2016)
missions overall or on a per-operator basis to allow commercial insurers to adequately determine and price operational risk for insurance purposes. Gilbert has studied the risk sharing model used by the nuclear industry, which features retroactive liability pooling, for potential applicability to space debris [52].

Addressing these concerns does provide some limitations on ADR efficacy versus a scenario driven only by engineering constraints, but these limitations are not so large as to render an ADR AMC unfeasible or unworthwhile. This is particular true since an ADR AMC is motivated by a desire to foster development of a competitive ADR marketplace, adequate ADR capacity, and socially efficient purchase quantities, not simply the mitigation of collision risk for objects removed under AMC subsidy. Furthermore, the development of an active commercial ADR marketplace and routinization of ADR can help set useful precedents and norms and may eventually induce the relaxation of some of these concerns.

E. Conclusions

It remains an open question whether the commercial voluntary business case for ADR will ever close for a commercial satellite operator purchasing such services. Nevertheless, an AMC offers the best chance to yield a functional ADR marketplace, simultaneously accelerating the availability of ADR for government clients, and decreasing the cost of an eventual forward-looking remediation mandate for satellites that fail to comply with debris mitigation guidelines. Debris mitigation will almost always be cheaper than ADR but will never be fool-proof and does not address existing debris.

An AMC would:

1) Increase the rate at which ADR technology is developed and becomes commercially available;
2) Decrease the price of ADR services within the market once they are developed and offered; and
3) Incentivize economies of scale to make ADR a plausible last resort for failed satellites and something that could be reasonably required by launching states for operators.

The current lack of action to remediate the orbital debris environment is increasing operational risk for current and future satellites and awaits imminent future collisions between massive objects in high LEO. The proposed ADR AMC would address this issue and spur the availability of ADR services for commercial operators.

At the same time, more domain-specific work is necessary to transition the AMC model to the space debris context. This process, progressing from a concept to work by a group of experts to develop an implementable proposal, would mirror the process for the PCV AMC. In particular, modeling is needed to assess reasonable time to market for ADR technology, cost of such capabilities, operator and government willingness to pay, and capacity requirements. At a theoretical level, work is also needed to understand the consequences of the anticipated higher marginal unit cost of ADR technology as compared to vaccines for program design, market power concerns in the ADR marketplace, and the consequences of an AMC that blends technologically near and distant approaches. Congress and the Biden Administration should fund work to further develop this knowledge and to then implement an ADR AMC program based on these findings and recommendations.

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F. Acknowledgments

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References


The US-China Relationship in the Space Sector

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Abstract—The relationship between the United States and China in the space sector over years is complex. Initial collaborations between the two countries took the form of Chinese launch services for US communications satellites in the 1980s. However, entering the 2000s, the United States Congress has announced multiple bans against scientific and civil space collaboration with China due to various sources of concerns. One defining incident that affected the US-China space relationship is the "Wolf Amendment" that was introduced to the Commerce, Justice, Science, and Related Agencies (CJS) bill in 2011. In this paper, we outline the history of the US-China relationship in the civilian space sector, and address the "Wolf Amendment" with its impacts on the US, China and global space community. We also explore future policy recommendations in order to promote a more collaborative and less conflicting US-China space relations atmosphere in the civil space exploration sector. These policy recommendations range from revision to the Wolf Amendment for collaborations in certain fields, new bilateral agreement between the two countries, US Congressional champions, and enhancement of academic exchange.

1. Introduction and Summary Findings

The US-China relationship in the space sector has been complicated since the 1980's up until this moment. Despite the initial commercial space collaborations mostly in the form of Chinese launch services for US communications satellites, entering the 2000s, multiple bans have been announced by the United States Congress against scientific and civil space collaboration with China due to concerns of defense, national security, espionage activity and human rights violations. One of the key incidents that affected the US-China space relationship is the "Wolf Amendment" that was introduced to the Commerce, Justice, Science, and Related Agencies (CJS) bill in 2011 [1].

In this paper, we outline the background of the US-China relationship in the civilian space sector, and address the "Wolf Amendment" and its major impacts on the US, China and global space community. We also explore future policy recommendations to promote a more collaborative and less conflicting US-China space relations atmosphere in the civil space exploration sector.

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Key Policy Recommendations:

- With the understanding of the importance of the Wolf Amendment in US defense and national security space, we recommend against a full repeal of the Amendment.
- Given the negative global impacts, as well as the administrative and political barriers that the Wolf Amendment has created, we propose a revision to permit the existence of certain types of space and aeronautics collaboration where interests are aligned between the US and China, in the areas of:
  - Human spaceflight and lunar exploration missions
  - Planetary and Earth Science
  - Space traffic management
- We propose that any new agreement for US-China space collaboration shall have the following hard requirements for both sides to clearly understand and be willing to abide by:
  - Transparency
  - Reciprocity
  - Mutual Benefit
- Understanding the US Congress’s processes, we propose identifying key Congressional members to champion international, civilian space collaboration and/or support an open and collaborative US-China relationship as one of their top three priorities among their legislative priorities.
- Under the current political atmosphere, we recommend prioritizing the protection of international students from China from immigration policies that might prevent them from studying in the US, since academic training is the base for any future space collaboration and critical for the advancement of science towards global welfare.

2. Background

2.1. US-China Relationship: Context and Key Events

- In the 1980s and 1990s, there have been US-China commercial space collaborations, in the form of Chinese launch systems transporting US-manufactured satellites to orbit. From 1988 to 2000, the China Great Wall Industry Corporation (CGWIC), the official vendor for Chinese space program, launched 27 foreign-made satellites. Among which, at least four are US-manufactured communications satellites, including three satellites manufactured by the Hughes Aircraft Company and launched on Long March rocket booster in 1990, backed by President Reagan and Bush [2, 3, 4].
- The commercial satellite launch service opportunity came to an abrupt stop after a launch failure in 1996, which was followed by a controversial multi-stakeholder investigation and allegations from both sides, leading to no further US export licenses granted for sending communications satellites to China since [4].
- China has long expressed interest in participating in the US-led international Space Station (ISS) but was denied by the United States to join [4].
- In 2011, former U.S. Rep. Frank Wolf (R-Va.) introduced a provision to the annual Commerce, Justice, and Science (CJS) bill, commonly known as the “Wolf Amendment.” The provision restricts organizations such as NASA, OSTP and National Space Council from working with China or any Chinese-owned company in a variety of activities. Similar languages have since been embedded in the following fiscal year CJS bills, including the 2020 appropriations bill (Section 519, CJS) [5].
- Throughout the years, space security topics such as anti-satellite (ASAT) have also stirred controversy between the two countries and the broader global space community, including the 2007 Chinese anti-satellite missile test at Fengyun-1C satellite and the 2008 US anti-satellite missile at USA-193 satellite. Historical and recent ASAT incidents by Russia and India also increased tension in the global space community [6, 7, 8, 9].

The relations between the two countries in the space sector over years have been complicated. However, there have been efforts by civil space actors from both sides to encourage possible collaborations. Table 1. shows a list of the past interactions between NASA and China over the last two decades. Below are few of the key events.
NASA has reported past low level scientific cooperation, data exchanges and participation in multilateral coordination groups with China [4].

In January 2004, President Bush announced a new Vision for Space Exploration for NASA to focus its activities on returning humans to the Moon and in preparation for landing on Mars, with an invitation to other countries to join. In November that year, NASA sponsored an “international exploration workshop” for countries interested in the Vision, which Chinese space officials participated in. The head of the Chinese space agency, Laiyan Sun, made a courtesy call on Mr. O’Keefe, the then NASA administrator. In January 2005, the trade publication Aviation Week & Space Technology (AW&ST) quoted Mr. O’Keefe as supporting cooperation with China: “The Bush Administration now believes that ‘measured and appropriate levels of space cooperation with China’ are viable” [4].

During the 2018 International Aeronautical Congress in Bremen, current NASA Administrator Jim Bridenstine showed interest in enhanced cooperation with China, including a meeting with Zhang Kejian, administrator of the China National Space Administration [14].

NASA and Chinese scientists collaborated in an attempt to coordinate the Chang’e-4 lunar far side landing in January 2019. NASA’s Lunar Reconnaissance Orbiter was unable to view the landing, but image the site during its next pass [14].

U.S. and Chinese officials are working towards meeting for a bilateral Civil Space Dialogue around March 2020. The last discussion of this kind was in 2017. The U.S.-China Civil Space Dialogue was established through the U.S.-China Strategic and Economic Dialogue in 2015, with an aim to enhance cooperation and transparency in the face of Congressional barriers to NASA engaging with China [11].

Table 1: Past interactions between NASA-China Interactions (2004-2020)

<table>
<thead>
<tr>
<th>Year</th>
<th>Key interactions/Events</th>
<th>Attitude/Details for Collaboration</th>
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<tbody>
<tr>
<td>2004</td>
<td>Administrator Sean O’Keefe hosted the CNSA Administrator at NASA Headquarters as a courtesy visit [12].</td>
<td>Courtesy visit without official proposal or discussion</td>
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<td>2006</td>
<td>Administrator Mike Griffin was the first acting NASA administrator to visit China and meet with CNSA leaders and Chinese Academy of Sciences members. This trip also included a tour of some of China’s space facilities [13].</td>
<td>An introductory trip to get acquainted, gain general understanding of the Chinese space program with initial discussions but not promises on possible collaborations on human space flight (post-space shuttle era), science and robotics missions [13]. Four-point proposal issued by China to establish ongoing dialogue between CNSA and NASA with annual exchanges and confidence building measures though no follow-up activities were announced [14].</td>
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<tr>
<td>2007</td>
<td>Engagement with Chinese counterparts was halted</td>
<td>After the Chinese anti-satellite weapon test which destroyed a decommissioned Feng Yun weather satellite [15].</td>
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<td>2008</td>
<td>Engagement activities resumed with the bilateral working groups with representatives from CNSA and NASA convening on the topics of Earth and space science [15].</td>
<td>NASA's tagline was that these working group meetings were “based on the principles of mutual benefit, reciprocity, and transparency” [16]. NASA stated that before any action could occur, a careful review process within the US government will be done on any project proposals with CNSA that resulted from these working group sessions.</td>
</tr>
<tr>
<td>Year</td>
<td>Event Description</td>
<td>Notes</td>
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<tr>
<td>2010</td>
<td>NASA Administrator Charles Bolden led a small delegation to China at the direction of President Obama and met with his counterpart at the China National Space Administration to review the ongoing efforts of Space and Earth Science working groups, established in 2007, to explore areas of mutual interest [17].</td>
<td>Bolden said, &quot;I am pleased that NASA was able to meet its objectives for the visit, which included becoming acquainted with relevant Chinese space officials and institutions, better understanding Chinese human spaceflight programs and plans, and reaching a common understanding of the importance of transparency, reciprocity and mutual benefit as the underlying principles of any future interaction between our two nations in the area of human spaceflight. &quot;Although my visit did not include consideration of any specific proposals for future cooperation, I believe that my delegation's visit to China increased mutual understanding on the issue of human spaceflight and space exploration, which can form the basis for further dialogue and cooperation in a manner that is consistent with the national interests of both of our countries&quot; [17]. In an interview for this paper, Bolden further explained the details of this visit, “It was during this visit that we shared with the Chinese the draft International Docking Standards that we hoped they would adopt for inclusion in the design of their future human spacecraft Shenzhou and Tiangong to make them compatible with docking to the ISS and international spacecraft respectively” [18].</td>
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<td>2011</td>
<td>The bilateral working groups were permanently suspended after Congress passed restrictions on collaboration with China.</td>
<td>NASA only interacts with its Chinese counterparts through multilateral discussions and events such as the International Space Exploration Coordination Group (ISECG).</td>
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<td>2013</td>
<td>At a multilateral panel in Beijing in September, a CNSA representative stated that CNSA was still waiting on an invitation to become a full member of the ISECG [19].</td>
<td>NASA Administrator Charles Bolden and other agencies stated that China is already part of the ISECG.</td>
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<td>2014</td>
<td>In January, Administrator Bolden met with his CNSA counterpart, Administrator Xu, but not with CMSA Director General Wang Zhaoyao, a PLA officer at an International Space Exploration Forum and a Heads of Space Agencies Summit in Washington, DC [20].</td>
<td>A Chinese delegation consisting of CNSA and CMSA officials were attending the event [21].</td>
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<tr>
<td>Year</td>
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<tr>
<td>2014</td>
<td>NASA Administrator Charles Bolden meets his Chinese counterparts meeting Nov. 9-10 of the International Forum for Aviation Research in Zhuhai, China, chaired by Jaiwon Shin, NASA associate administrator for aeronautics, discussing cooperation in the areas of Earth sciences and aeronautics [22]. NASA had not previously disclosed Bolden’s visit to China. A statement on the Chinese-language website of China’s State Administration of Science, Technology and Industry for National Defense, said there was a “frank exchange of views” between Bolden and Xu and the two “agreed to strengthen communications and exchanges” between the nations, but did not go into detail about the topics they discussed. “We heard their story,” Bolden said. “It was mainly a listening opportunity.”</td>
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<td>2016</td>
<td>NASA Administrator Charles Bolden visited China in August, and he met with officials from CAE and the Civil Aviation Administration of China (CAAC) [23]. The details of the Air Traffic Control agreement were discussed.</td>
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<td>2016</td>
<td>NASA and China to collaborate on Air Traffic Management Research. NASA and the Chinese Aeronautical Establishment (CAE) have signed a memorandum of understanding to cooperate on aeronautics research that will advance air transportation automation for U.S. and Chinese aviation operations in China [23]. After many years of work, the Air Traffic Control agreement was secured. Dava Newman, former Deputy Administrator of NASA, says, &quot;It's not 'space', but we made a calculated decision to go after a 'win', in terms of getting a true agreement with China for Air Traffic Control, signed a major agreement, and we viewed this as our first step in enhanced relations and foundational to moving on to civil space relations&quot; [24].</td>
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<td>2016</td>
<td>Former Deputy Administrator of NASA, Dava Newman, was on a trip to China to present for the WEF [24].</td>
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<td>2018</td>
<td>During the International Aeronautical Congress (IAC) in Bremen, NASA Administrator Jim Bridenstine showed interest in enhanced cooperation with China including a meeting with Zhang Kejian, administrator of the China National Space Administration [10].</td>
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<td>2019</td>
<td>Talking about NASA's hopes to have all the current ISS partners involved in the Gateway and overall Artemis program at a press conference, Bridenstine hedged when asked if China could participate, &quot;If that were to change, it would be above my pay grade,&quot; he said [25].</td>
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2.2. Major Players on Both Sides

In discussing the US-China space relationship, we will focus on the major players on both sides.

- **NASA** is the independent US federal agency that is responsible for science and technology related to civilian air and space. It is subject to the immediate restriction of the Wolf Amendment as a budgetary constraint, along with the Office of Science and Technology Policy and National Space Council [26].

- **China National Space Administration (CNSA)** is the most similar counterpart to NASA on the Chinese side, whose responsibilities include “the management of space activities for civilian use and international space cooperation with other countries, and performs the corresponding governmental functions” [27].

- CNSA oversees the **Chinese Society of Astronautics**, an non-governmental and nonprofit academic organisation and corporate aggregate, perhaps a proxy to the American Institute of Aeronautics and Astronautics (AIAA) [28]. It has organized the 47th and 64th International Aeronautical Congress in 1996 and 2013, as well as the Global Space Exploration Conference in 2017.

- **Chinese Academy of Sciences (CAS)** is a merit-based learned society and a system of higher education, comprising 104 research institutes, 12 branch academies, three universities and 11 supporting organizations across the country. CAS “considers international cooperation as a recipe for its success and an effective means to advance science and to address global challenges” [29]. Up till January 2020, CAS has signed collaborative agreements with 174 organizations in 61 countries, including young scholar exchange programs and multiple research projects with US scientists on high energy physics [29, 30]. The National Space Science Center of the Chinese Academy of Sciences and the Space Studies Board of U.S. National Academies of Sciences, Engineering, and Medicine have also co-hosted the Forums for New Leaders in Space Science since 2014. These forums have three-folded objectives: 1. To identify and highlight the research achievements of the best and brightest young scientists currently working at the frontiers of their respective disciplines; 2. To build informal bridges between the Earth- and space-science communities in China and the United States; and 3. To enhance the diffusion of insights gained from participation in the Forum to the larger Earth- and space-science communities in China and the United States [31]. Many view the National Space Science Center of the CAS as an equivalent to NASA’s Science Mission Directorate.

- Two other important players in the Chinese space sector are the **China Aerospace Science and Technology Cooperation (CASC)** and the **China Aerospace Science and Industry Cooperation Limited (CASIC)**, both are state-owned enterprises succeeding from military ministries. CASC is a Global Fortune 500 Firms with specialization in the research, design, manufacture, test and launch of space products such as launch vehicle, satellite, manned spaceship, cargo spaceship, deep space explorer and space station as well as strategic and tactical missile systems [32]. CASIC has research and product portfolio in air defense missile weapon system, aerodynamic missile weapon system, solid launch vehicle and space technology products [33].

- In the aeronautics sector, the **Chinese Aviation Establishment (CAE)** is a state-owned, government-sponsored aeronautics research organization and key coordinator of bilateral and multilateral cooperation in aeronautical science and technology. In 2016, CAE and NASA signed a memorandum of understanding (MOU) for a five-year collaborative effort on air traffic management research initiatives, in collaboration with the International Forum for Aviation Research (IFAR) [18, 34, 35].

3. Analysis

3.1. Wolf Amendment: History and Background

Annually, several appropriations measures that provide discretionary funding for numerous activities, such as national defense, education, and homeland security, are considered through the *congressional appropriations process* in Congress [36]. These appropriations measures fall under the jurisdiction of the House and Senate Appropriations Committees, and have recently provided approximately 35% to 39% of total federal spending, while the remainder is mandatory spending (including social security, Medicare, Medicaid…) controlled by House and Senate legislative committees, in addition to net interest on the public debt [36]. There are two separate types of measures for discretionary funding established in Congress: authorization bills and appropriation bills. As defined by Saturno et al, “These measures perform different functions. Authorization bills establish, continue, or modify agencies or programs. Appropriations measures subsequently provide funding for the agencies and programs authorized. There are three types of appropriations measures. Regular appropriations bills provide most of the
funding that is provided in all appropriations measures for a fiscal year and must be enacted by October 1, the beginning of the fiscal year" [36]. There is a joint jurisdiction over all appropriations bills in the United States Congress, each of the House and Senate Committees on Appropriations has 12 matching subcommittees responsible for developing one of the twelve annual regular appropriations bills [36].

The United States House Appropriations Subcommittee on Commerce, Justice, Science, and Related Agencies (CJS) is one of the US House subcommittees and is within the US House Committee on Appropriations. It has jurisdiction over the budgets of the Departments of Commerce and Justice and several independent agencies, including the National Aeronautics and Space Administration (NASA) and the National Science Foundation (NSF) [29]. The CJS Appropriations Act makes investments for each fiscal year to support law enforcement, economic prosperity, scientific research, space exploration, and other national priorities [37].

In 2011, Representative Frank Wolf (R-VA) introduced the so-called "Wolf Amendment". As the former NASA administrator Major General Charles Bolden explain in an interview for this paper with, "The primary driver for the Wolf Amendment was Congressman Frank Wolf’s strident dedication to human rights and his belief that we (the US) could isolate China to the extent that they would come around and improve their performance in compliance with international human rights standards/norms" [18]. This amendment has continued to be included in the annual CJS appropriations bill including this fiscal year [1]. It’s an unprecedented law whose main purpose is targeted on restricting the collaborations between U.S. government agencies like NASA, OSTP and National Space Council with Chinese commercial and governmental agencies—significantly hindering any bilateral civil space projects [1, 5].

The "Wolf Amendment" in Sec. 529 of CJS appropriations bill states [5]:

"(a) None of the funds made available by this Act may be used for the National Aeronautics and Space Administration (NASA), the Office of Science and Technology Policy (OSTP), or the National Space Council (NSC) to develop, design, plan, promulgate, implement, or execute a bilateral policy, program, order, or contract of any kind to participate, collaborate, or coordinate bilaterally in any way with China or any Chinese-owned company unless such activities are specifically authorized by a law enacted after the date of enactment of this Act.

(b) None of the funds made available by this Act may be used to effectuate the hosting of official Chinese visitors at facilities belonging to or utilized by NASA.

(c) The limitations described in subsections (a) and (b) shall not apply to activities which NASA, OSTP, or NSC, after consultation with the Federal Bureau of Investigation, have certified—

(1) pose no risk of resulting in the transfer of technology, data, or other information with national security or economic security implications to China or a Chinese-owned company; and

(2) will not involve knowing interactions with officials who have been determined by the United States to have direct involvement with violations of human rights.

(d) Any certification made under subsection (c) shall be submitted to the Committees on Appropriations of the House of Representatives and the Senate, and the Federal Bureau of Investigation, no later than 30 days prior to the activity in question and shall include a description of the purpose of the activity, its agenda, its major participants, and its location and timing."

3.2. Wolf Amendment: Global Impact

Most discussions around the Wolf Amendment have been centered on the impacts on either the US and China, while a holistic and global perspective has been neglected but remains equally important. Several scholars and experts have expressed different opinions on how such a bilateral policy might have spill-over effects on the global space community on various occasions [38, 39, 40]. In summary, the Wolf Amendment has global impacts on:

- **Creating an impression that space is no longer a multilateral environment**, particularly by blurring the lines between military and civilian space. “The Wolf Amendment ultimately undermines an international culture of multilateralism in [civil] space by sowing distrust between major space superpowers, increasing
the potential for misunderstandings and tensions given their lower levels of continued communication and cooperation on [civil] space-related issues” [38].

- **Increasing number of international space cooperation projects** between China and space faring countries other than the US since the inception of the Amendment, offsetting the initial policy objectives [39, 40]. Between 2011 and 2016, China has signed 43 space collaborative agreements or memorandum of understanding with 29 countries, agencies and international organizations, including ESA, Russia, Germany, France, Italy, United Kingdom, Netherlands, India, Brazil, Indonesia, Algeria and many others [41].

- **Equating China with the Soviet Union**, despite the vast difference between them, particularly in the context of today’s globalized world versus the post-World War II world [39]. This Amendment also undermines and creates confusing international space collaboration narratives for NASA and its existing partners, including Russia and Europe.

- **Further decentralizing international space governance** with ambiguous outcomes for developing space faring countries. The Wolf Amendment has formed an effective perception that the two nations “do not, and should not, work together.” [40] As international space policy trends towards non-binding “soft” agreement and national level best practices laws rather than rigid international treaties, as well as space development efforts towards militarized and fragmented between emerging space countries and space-faring countries, the roles and actions of perceived leaders will become more influential [42]. This current space era is more decentralized than before due to the absence of strong international space treaties and implementation, as well as divergent demands of space-faring and non-space-faring countries. If the U.S. and China are forced to work separately, the possibility of the two sides competing for partners and resources will either create more opportunities for other actors to get involved or eliminate participation from all in the long-term [40].

As outlined above, the "Wolf Amendment" has major impacts on the US, China and global space community, most of which are negative. Our general direction is towards a different scenario of US-China space relations, one that is more collaborative and less isolating and conflicting.

### 3.3. Willingness of Key Players

China has been very interested in international cooperation in space. The 2000 White Paper on Chinese Space discusses it extensively, and China has cooperative arrangements with several countries, including Russia, Brazil, and Europe [4]. The 2016 White Paper on Chinese Space mentions the current relationship with the US as: “under the framework of the U.S.-China Strategic and Economic Dialogue, (US and China are) initiating conversations on the civil space sector, establishing goals to strengthen cooperation on areas such as space debris, space weather and global climate changes” [43]. Compared to the extensive international space agreements and projects with other countries listed earlier, this language on US relationship indicates the current limited access of collaboration but wish to strengthen it.

As illustrated in Table 1, the various interactions between leadership of several NASA administrations and CNSA demonstrated the consistent willingness to cooperate from the Chinese side, whether through visiting sites, joining multilateral working groups, or directly asking to join projects such as the International Space Station. As China space emerged into human spaceflight capability in 2008, the collaborative attempts from both sides were also most aggressive during that decade, with examples of running bilateral working groups with representatives from CNSA and NASA convening on the topics of Earth and space science from 2008 to 2010, before Congress permanently suspended them and passed restrictions on collaboration with China [15, 24]. In an interview for this paper with Major General Charles Bolden, the former NASA administrator, he commented, “during this period, China was an active, though non-signatory, participant in the development of the initial Global Exploration Roadmap (GER) that sets out international consensus on the pathway for human deep space exploration, establishing Mars as the ultimate goal for international human exploration” [18]. In addition, there were multiple trips led by Major General Charles Bolden meeting with the counterparts at CNSA in occasions such as the International Space Exploration Coordination Group (ISECG) [19], International Space Exploration Forum [20], International Forum for Aviation Research [22], and Air Traffic Management Research [23]. “[However] Their participation in the subsequent ISECG meetings and revised GER editions has been somewhat spotty,” said Major

In more recent years, there have also been signs and actions showing the willingness to collaborate from the Chinese side and NASA. By “keeping the door open”, as current NASA Administrator Jim Bridenstine expressed, is a way to enhance US soft diplomacy with a key player in the space realm. During the 2018 International Aeronautical Congress in Bremen, NASA Administrator Jim Bridenstine showed interest in enhanced cooperation with China, including a meeting with Zhang Kejian, administrator of the China National Space Administration [4]. NASA and Chinese scientists collaborated in an attempt to coordinate the Chang’e-4 lunar far side landing in January 2019. NASA’s Lunar Reconnaissance Orbiter was unable to view the landing, but image the site during its next pass [14]. U.S. and Chinese officials are working towards meeting for a bilateral Civil Space Dialogue around March 2020. The last discussion of this kind was in 2017. The U.S.-China Civil Space Dialogue was established through the U.S.-China Strategic and Economic Dialogue in 2015, with an aim to enhance cooperation and transparency in the face of Congressional barriers to NASA engaging with China [15].

Despite the changing administrations in NASA and the US with various levels of collaboration intentions, the willingness to collaborate with the US and NASA from the Chinese side has been consistent during the two administrations of CNAS, under the leadership of Mr. Xu and Zhang [10, 17]. Several NASA administrations and their efforts can also serve as a roadmap and examples of re-initiating partnership, such as the NASA leadership during the Obama Administration.

The progress in moving towards a more fluid and potentially collaborative space relationship between the US and China has been slow and non-systematic, oftentimes disrupted by the fluctuating political situation of the two countries. International space collaboration, particularly civilian space collaboration, is the cornerstone for trust and peaceful use of space. The US-Russia relationship is a clear parallel comparison. However, it's important to remember that in this case of Russia, the political will of the two countries' political leadership (rather than NASA) dictated the Apollo-Soyuz at the height of the Cold War, setting the stage for high-level diplomacy for the ISS partnership [44, 45].

In an interview with the Senior Policy Advisor in the MIT Washington Office Dr. Kate Stoll, who spoke in her personal capacity, not on behalf of MIT or the MIT Washington Office, discussed the parallel comparison between the US-Russia and the US-China space relationships and the chances of replicating such a collaborative relationship between the US and China by saying,

"In general, defense hawks are defense hawks, against everyone who's not considered an ally, but I think people are very aware that China and Russia pose two very different kinds of challenges for America. Russia was a space competitor, but not an economic competitor. We were never worried that their economy would interfere or rival America's economy. But with China, it's a huge economy. They have a lot of control over the global supply-chains, and they have amazing research, doing all kinds of cutting edge in every field, so they truly are rivals in many ways, so it's pretty different than Russia. Once it was clear that America was dominant in [space,] then it didn't feel as risky to collaborate with them [Russia]. The space race was also a matter of pride” [46].

4. Key Findings and Policy Recommendations

Here we present our key findings and policy recommendations after reviewing the history and referring to relevant discussions and interviews from experts.

1. **Policy Recommendation #1**: With the understanding of the importance of the Wolf Amendment in US defense and national security space, we recommend against a full repeal of the Amendment.

2. **Policy Recommendation #2**: Given the negative global impacts, as well as the administrative and political barriers that the Wolf Amendment has created, we propose a revision to permit the existence of certain types of space and aeronautics as collaboration where interests are aligned between the US and China, in the areas of:
   a. Human spaceflight and lunar exploration missions
3. **Policy Recommendation #3:** We propose that any new agreement for US-China space collaboration shall have the following hard requirements for both sides to clearly understand and be willing to abide by:
   a. Transparency
   b. Reciprocity
   c. Mutual Benefit

4. **Policy Recommendation #4:** Understanding the US Congress’s processes, we propose identifying key Congressional members to champion international, civilian space collaboration, starting with those who are more collaborative in research realms or in favor of diffuse tensions between the two countries and/or support an open and collaborative US-China relationship as one of their top three priorities among their legislative priorities.

5. **Policy Recommendation #5:** Under the current political atmosphere, we recommend prioritizing the protection of international students from China from immigration policies that might prevent them from studying in the US, since academic training is the base for any future space collaboration and critical for the advancement of science towards global welfare.

5. **Discussion**

In this section, we discuss the above findings and policy recommendations in more details, with a focus on the "Wolf Amendment"—its possible benefits and proposed revisions, in addition to other recommendations to collectively promote a more collaborative and less conflicting US-China space relations atmosphere in the civil space exploration sector.

5.1. **Policy Recommendation #1:**

Despite the wide variety of negative global impacts that the "Wolf Amendment" imposes on the US, China and global space community, there are still benefits for preserving parts of this amendment, especially in the areas of defense and national security. As the chair of the FAA’s Commercial Space Transportation Advisory Committee (COMSTAC) Mike Gold notes, “A lot of people think the Wolf Amendment is a prohibition on working with the Chinese. It’s not, It says that you can work with China, but you need certification from the FBI—again totally warranted—and notification of Congress. Is that a prohibition?” he asked. “To me, those are two common sense steps right now. NASA can engage with China, has engaged with China under the auspices of the Wolf Amendment” [47].

Thus, it’s clear that this amendment provides the US with the benefit of having an extra layer of national security, so it should not be fully repealed. It is important to preserve its scrutiny for certain projects to avoid unwanted exchanges of technology or problems with other existing US space partners. Todd Harrison, the director of the Aerospace Security Project at the Center for Strategic and international Studies, explains this saying, “As we engage China more openly in civil space, we should simultaneously make a concerted effort to improve our deterrence posture in national security space” [47].

5.2. **Policy Recommendation #2:**

Many argue that the legal interpretation of the “Wolf Amendment” is not a total prohibition of US-China space and aeronautics collaboration. However, realistically, the prevention of hosting official Chinese visitors in NASA facilities, extended procedures in acquiring certification from the FBI and notification of Congress have created enough administrative and political barriers against any collaborations to happen. With full understanding of the complications and a hope for a peaceful and collaborative space and aeronautics environment, we propose a modification to the “Wolf Amendment” to permit the existence of certain types of space and aeronautics collaboration where interests are aligned between the two countries.

- **Human spaceflight and lunar exploration missions:** The two countries clearly share aspirations in these resource-intensive missions (see Table 2 for comparison). Collaboration on these fields is more likely to lead to success for either party with better management of resources.
- **Planetary and Earth Science**: As prior landing collaboration between NASA’s Lunar Reconnaissance Orbiter and Chang’e demonstrated, collaborations between scientists in fields of planetary science posed no threats but benefits [47]. NASA and the Chinese Academy of Science’s collaboration in the SERVIR Himalaya’s Program with USAID also remains a strong contributor to understanding earthquakes and glacial activity in the Himalayan region [18, 48]. The U.S. and China should further capitalize on these scientific discoveries and translate them into actionable climate restoration initiatives or other global crisis solutions, such as combating COVID-19. Such joint endeavors will establish common ground that both diplomatic hawks and doves can agree upon [49]. An example of such bi-lateral collaboration is the China-Brazil Earth Resource Satellite cooperation program (CBERS), where the two countries jointly researched and developed six remote sensing satellites for resource exploration, environmental protection monitoring, climate change research, disaster prevention and mitigation [50].

- **Space and Air traffic management**: Continued collaboration in the area of “air traffic management” will prove beneficial to the international aviation community [18]. Additionally, on the side of "space traffic management", top leaderships from both NASA and CNSA have expressed collaborative interests on this topic [46]. Isolation on traffic management has led to catastrophic consequences on land, sea and airspace before—it should not be replicated in space.

We believe tactical and incremental shifts on key missions as suggested above should be the starting point and compromises necessary for both sides to make.

Major General Charlie Bolden stresses that during his NASA administration, they were working effectively with China in aeronautics, mostly in air traffic management; in the science, particularly in glacial characterization in the Himalayas; in addition to partnering with them on a seismology program sponsored by NASA and the US agency for international development. He explains,

"*We [NASA] complied very strictly to these stipulations to allow us to conduct certain bilateral activities with Chinese entities in the areas of science, aeronautics and robotic space exploration*” [18].

"*So other than in space flight, we got to the point that we were able to work very effectively with them, and we did it with the consent of the Congress and the Administration, but it took understanding what the problem was, understanding what everybody's concerns were.*" Maj. Gen. Bolden adds, "*My rationale with Congressman Wolf was: 'Okay, I agree with you about human rights, but would you rather have NASA just completely ignore China, or would you rather have me in the room with them, talking to them, trying to get them to have people see how we live, and how we do things, and let them at least have the opportunity to see what a democratic government is like?'” [51].

“Continued collaboration in the area of air traffic management will prove beneficial to the international aviation community. The MOU signed in 2016 between NASA and the Chinese equivalent of the FAA, the Chinese Aeronautical Establishment (CAE) allowed (their) collaboration with NASA ARMD on air traffic management initiatives in collaboration with the IFAR. We were also able to bring China into the International Forum for Aviation Research (IFAR) where they are represented by the CAE and at one time held the presidency of the IFAR” [18].

<table>
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<th>Goal (year)</th>
<th>China/CNSA</th>
<th>U.S./NASA</th>
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<tr>
<td>2020</td>
<td>Launch a Mars probe, orbit Mars, return to Mars surface</td>
<td>First successful commercial launch of NASA astronauts from the U.S. on SpaceX Crew Dragon spacecraft [52]</td>
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<td></td>
<td><em>Shenzhou</em>: Send astronauts to the Moon</td>
<td>Launch Mars 2020 Rover with a Mars helicopter</td>
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<td>Starship unmanned spacecraft mission to reach Mars orbit</td>
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In a conversation with Professor Dava Newman, the former Deputy Administrator of NASA, she also commented on the wording of the Wolf Amendment, especially Section (c) (1) that states "(c) The limitations described in subsections (a) and (b) shall not apply to activities which NASA, OSTP, or NSC, after consultation with the Federal Bureau of Investigation, have certified—(1) pose no risk of resulting in the transfer of technology, data, or other information with national security or economic security implications to China or a Chinese-owned company.". Prof. Newman notes,

"This is tricky wording: "pose no risk". How do you assure 0% risk? There is already a lot of data and technology transfer and in some cases espionage (much less for NASA than in the DOD space). Safer territory is staying away from national security and playing in the civilian arena where tech transfer and data securities can be, and are, put in place" [24].

Dr. Kate Stoll also discussed operationalizing this policy recommendation saying,

"The way to approach the change is that CJS appropriators would have to decide to add the Wolf amendment in an altered form. As you know, they can just not add it [Wolf amendment] to the next appropriations bill if they want to, but that's not gonna happen. So the way to go about it is to say 'We realize that this is something that is still politically popular, but with this additional language in this amendment, it could narrow it in a way that's not so all encompassing and so broad that it kills all collaboration'" [46].

After consulting with experts on this topic, we also propose the following three recommendations, in parallel with modifications of the Wolf-Amendment.

5.3. **Policy Recommendation #3**

We propose that any new agreement for US-China space collaboration shall have the following hard requirements for both sides to clearly understand and be willing to abide by:

1. Transparency
2. Reciprocity
3. Mutual Benefit

Major General Charlie Bolden truly believes in these three pillars as hard requirements to ensure a successful relationship between both countries as he explains,"Under the mantra of “Constancy of Purpose”, these three critical requirements for collaboration remain absolutely necessary to provide continuity from one US Administration to the next in laying the groundwork for US-China collaboration" [18, 51]. However, we realize the difficulty in making these requirements verifiable on either side. As Dr. Kate Stoll said while discussing operationalizing this policy recommendation,

"The thing about transparency is that it's hard to verify, and if you don't trust the other person in the partnership, then transparency is just a word, and it doesn't mean anything. So I feel like a lot of members of Congress would say 'China
hasn't been transparent on many other things, why would we trust them to be transparent on this?’, the skepticism would be pretty high among members of Congress” [46].

Dr. Stoll also suggested, "Another approach would be to emphasize the many other ways in which the US protects itself—including export controls and ITAR—that are independent of the Wolf amendment. Explain the ways in which we are already careful about how we interact with foreign countries and foreign collaborators. Emphasize that the Wolf amendment chills all collaboration with China in space, even the parts that are beneficial to the US. Could we instead rely on the specific policies that we have already set up to make sure that we're being careful in these collaborations?"

She adds, "Another consideration is that people conflate civil space collaboration with defense and security issues. It is true that they are different, but to play the devil’s advocate, there are a lot of dual-use applications, so it is really hard to know ‘Are they really using this for research?’, or ‘Are they using this for other reasons including reconnaissance?’ That’s one reason why space is so challenging."

As a comparison and an example of how this recommendation might be operationalized, CGWIC, the official commercial organization acting as a vendor and a subsidiary of China Aerospace Science and Technology Corporation (CASC), has stated similar guidance for their international collaboration projects. Posted on their website as the “Purposes and Principles” are [53]:

1. Equality and Mutual Benefits
2. Peaceful Utilization
3. Common Development

5.4. Policy Recommendation #4:

Understanding the US Congress’s processes, we propose identifying key Congressional members to champion international, civilian space collaboration and/or support an open and collaborative US-China relationship as one of their top three priorities among their legislative priorities. On the topic of US-China relationships, there are several members of Congress who "would never change their minds," as Dr. Kate Stoll says, "They would also be the people that would kill any bill or any proposals to not include the Wolf Amendment in the next appropriation."

Former Rep. John Culberson (R-TX) was the successor of Frank Wolf (R-VA) as chair of the Commerce-Justice-Science (CJS) subcommittee from 2014 to 2019. In his 2018 re-election campaign, he was defeated by Democrat Lizzie Fletcher, and therefore lost his chairmanship to the CJS Committee [54]. Dr. Stoll mentions that while there has been hope that with his leaving, there will be relaxation or chance for change in the Wolf Amendment [46]. However, given the external political environment and barriers in the Senate, the Wolf Amendment was again included for NASA FY2020 budget. Talking about Rep. Wolf and Rep. Culberson, Major General Charlie Bolden says,

"Congressman Wolf was a person that his passion was human rights, and so his purpose for avoiding any relations with China was "we will isolate them, so they come around and agree with us on human rights, agree with the US's position on human rights." His successor [Rep. Culberson] was a Congressman from Texas who had no principle, he just hated China, and he couldn't give you a reason for being opposed to working with them. So it's difficult to go in and kind of reason to somebody like that" [51].

According to Dr. Stoll, "There is a lack of motivation within the Senate and the House to eliminate the inclusion of the Wolf Amendment. Even those Congress members who are champions for research, especially space research, are really careful about this topic right now. ” Dr. Stoll also said that she doesn't think that the democrats on the CJS would "stick their necks out on this issue right now" [46].

5.5. Policy Recommendation #5:

Under the current political atmosphere, we recommend prioritizing the protection of international students from China from immigration policies that might prevent them from studying in the US, since academic training is the base for any future space collaboration and critical for the advancement of science towards global welfare. As Dr. Stoll explains,
“There are obviously some projects that international students from certain countries can’t work on such as those that are classified, but that’s not what most universities are doing. If it is open research that’s going to be published, then there shouldn’t be a restriction on which kinds of students can participate. If we disrupt immigration policy for international students coming into America—and Chinese students are a large part of that population—we’d be shooting ourselves in the foot. It’s not good for America to discourage smart people from all over the world to come and study with us, to innovate in America. But we do have to acknowledge the real challenges between the two countries right now. Immigration is critical but so is keeping science open as much as possible. If research needs to be secret, then you move it to a classified lab, and you keep everything on campus open, and continue to welcome international students to do research in America” [46].

5.6. Policy Viability

The current US-China relations are tense, specifically hard-line on the space sector and Chinese influence on universities. We understand the current environment is definitely not optimal for our policy recommendation to work out, but we hope by thinking about these issues beforehand, when the timing is right, there will be something ready. Hypothetically, if there were champions on both sides and political support from all around, a bilateral agreement could trump the Wolf Amendment. As Dr. Stoll says, “It has to be two factors: one is democrats have to have control and we need to be in a situation where it’s not so tense between the US and China which I believe we’re going to get there, but we don’t know when. Right now the timing is terrible, and thus we must wait for the right time” [46].

6. Conclusions and Future Work

From here, we conclude that despite the current political tension between the US and China and the isolated past in the space sector in the last two decades, there are clear benefits and urgency to continue the push for a peaceful and collaborative relationship between the two countries. Combining history, we learn the various efforts form civil space actors on both sides to promote collaborations. These actions serve as baseline and inspirations for our policy recommendations, hopefully to be adopted in the near future.

In order to refine these policy recommendations and adjust it to the current situations, we’ll continue our work in a Space Policy Group at MIT. We hope to conduct more extensive research on the past commercial satellite launch services between the two countries, as well as examine future civil space missions from both sides to identify possible collaborative areas and specific projects, including but not limited to astronaut participation, joint research, and commercial collaborations. We hope to interview multiple political science professors and space policy experts, and hopefully present these policy recommendations on the Hill in the future.

Acknowledgements

We would like to express our sincere gratitude for Professor Dava Newman for being an incredible resource for this research. This paper would have not been possible without her guidance, support and amazing efforts in the MIT 16.981 Space Policy Seminar class. Additionally, we cannot express enough thanks for Major General Charlie Bolden and Dr. Kate Stoll. Their resourceful input in the interviews was an integral part of this research.

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Evaluating Human Spaceflight Activities and Policy to Promote Terrestrial Human Health
Rachel Bellisle & Golda Nguyen

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1. Introduction and Summary of Findings

1.1 Motivation for Leveraging Human Spaceflight for Earth-based Benefits

The central theme of human spaceflight is focused on exploration and the desire to send humans to explore beyond the Earth. Historically, the objectives of human spaceflight have been driven by a desire for exploration and national pride or prestige. Mindell et al. argue that these are primary objectives that justify the significant risks to human life, and the presence of humans provides a greater benefit than cost [1]. Beyond these reasons, however, there remains immense value in “secondary objectives” of applying the knowledge and technologies used for spaceflight to Earth-based applications to promote economic development, scientific advancement, and social impact [1]. International Space Station (ISS) Expedition 34 captured this sentiment with the slogan “Off the Earth, for the Earth” [2], but this idea has continuously been put into action through a vast and diverse array of spaceflight research and development directed toward Earth applications dating back as far as the Mercury-Gemini era. While there are many valuable areas to highlight, this report will focus on human spaceflight activities related to human health applications on Earth.

1.2 Summary of Findings

The scope of this report focuses on US human spaceflight activities as conducted by NASA and its domestic partners. In addition to capabilities developed for human spaceflight, another key focus of the paper will be to discuss activities and research being conducted on the ISS National Lab (ISSNL) (the dedicated US segment of the ISS) as microgravity research is a critical spaceflight realm for conducting human health-related research and development.

In summary, successes in the translation of human spaceflight technologies to terrestrial human health applications largely encompass six categories:

1. Pharmaceuticals and Biotechnology
2. Improved Medical Devices and Techniques
3. Technologies for Tele-Health and Remote Locations
4. Advanced Assistive Devices
5. Improved Understanding of Human Physiology
6. Translatable Technology and Expertise for Emergency Response

Trends were observed in each category regarding different routes for technology implementation and translation to Earth applications. As a high-level finding, life sciences research, including pharmaceuticals and biotechnology, is highly reliant on the ISSNL to support commercial research in microgravity. The pharmaceuticals and biotechnology category also includes examples that showed the highest economic benefits of all items analyzed in this study. Beyond life sciences research, medical devices, assistive devices, and technologies for remote locations showed some similar trends in their routes to development, with most successful outcomes involving some type of external collaboration. This primarily includes 1) technology transfer after NASA technology development and/or 2) collaborations between NASA and a commercial or academic organization. It is clear that human physiology research has a high scientific value. While economic and social impact values in this category are difficult to measure, they are likely achieved as a secondary result of published discoveries. Translatable technology and expertise for emergency response by NASA and aerospace efforts is currently being highlighted during the COVID-19 crisis, but this knowledge and technology capacity has existed
for emergency response through past spinoff technologies, and can continue to deliver high social, economic, and scientific benefit when re-directed toward non-aerospace applications.

A common theme across NASA and ISSNL human health research and development activities has been the utilization of partnerships with external collaborators. NASA has over 2500 domestic partnerships which are largely grouped into four categories: government partners (federal agencies, national institutions or entities, state or local governments), industry, academia, and non-profit organizations. Across government entities, federal agencies lead in the number of NASA partnerships, with the Department of Defense (DoD) making up a quarter of the entire domestic agreements portfolio alone. NASA leverages various partnership types to manage programs and research activities and share, provide, or procure technology and services. However, data on human health partnerships is limited. Collaboration opportunities and synergies with government agencies and industry exist in human health areas, including emergency/combat care, operational medicine, clinical and rehabilitative medicine, biological sciences, radiation science. To ensure that research and resources are being maximized for terrestrial and ISSNL work, further documentation, publication, and widespread communication of the partnership avenues available to non-aerospace health/medical researchers. The establishment, amplification, or consolidation of joint working groups or discussion groups on translational research will further promote the full utilization of NASA and ISSNL resources for terrestrial human health benefits from spaceflight activities.

2. Background and Literature Review

2.1 Valuation of Spaceflight Activities

Human spaceflight stakeholders must consistently assess the value of US human spaceflight research activities. A review of several valuation methods [1, 3, 4] highlights a few key categories that return on investment in human spaceflight research may fall into:

- Advancement of US human spaceflight objectives
- Economic value and development for stakeholders
- Scientific value for tangential research and business activities
- Social impact value

The last three categories are often deemed as secondary to the primary directives laid out annually through the NASA Authorization Act. However, to help inform how research activities for human spaceflight are prioritized, it is beneficial to determine how value is measured in each of these “secondary” categories and what weight each category holds for a given activity. These secondary categories of valuation can highlight work that not only achieves NASA’s missions but simultaneously provides benefit back on Earth. Of course, there is no “one size fits all” metric for computing value for work across any of these dimensions, but quantitative measures can be used to guide decision-making processes and track the efficiency of resource utilization. Several metrics that have been used for evaluating current spaceflight research and technology transfer in these secondary dimensions are described below.

Economic value can be measured in terms of direct profit or revenue generated from a good/service, or in terms of the direct or tangential economic activity generated. Examples of these economic activity measures include jobs created, improvements to productivity/efficiency [3], market penetration, cost-benefit analysis, future industry outlook, and limitations on accessibility [4]. Scientific value can be evaluated in terms of academic value or the extent to which the knowledge generated is used. Such metrics could include the number of direct
publications from a research activity, the impact factor of those publications, the extent of national or global usage of the results, and the number of relevant disciplines to which the research output could be applied (e.g. Map of Science) [4]. Lastly, social impact value can be more difficult to define than the other two categories, as social impact is unique to a society or culture. At a broad level, social impact could be measured in terms of lives saved or improved [3] or in terms of the level of public engagement and interest in human spaceflight activities, such as enrollment rates in STEM fields or amount of community engagement activities.

2.2 Science in Microgravity

Pharmaceuticals and biomedical research in microgravity offer significant economic and scientific value. The most commonly cited example of economic benefit is a 2001 shuttle mission in which Amgen tested several drugs in the microgravity environment by assessing bone loss in mice. This experiment included a bone antiresorptive drug which was later named denosumab (brand name Prolia). Amgen’s Prolia was later FDA-approved in 2010 and has since become the leading drug for bone-health [4]. With revenues of $2.7 billion in 2019, Prolia now has the third-highest revenue of Amgen’s products [5], and in 2017, Prolia was used to treat more than 850,000 active patients [4]. Similar experiments are frequently seen on the ISSNL, where microgravity-induced bone or muscle loss in animal subjects is used to test potential drug candidates to address bone or muscle-related diseases on Earth. In general, microgravity can be used to model human diseases in both humans and animal models, allowing an analysis of these adaptations to microgravity and (in the case of animal models) providing a platform for testing potential therapies. The ISSNL also notes the value of experiments that aim to study gene expression changes (in humans or other organisms), investigating adaptations to the space environment and providing a greater understanding of human physiology which can be applied to benefit human health on earth [6]. Cell culture growth can also benefit from the microgravity environment. It is suggested that the 3D cell cultures grown in microgravity more closely replicate cells \textit{in vivo}, providing improved models for testing drugs, learning about cellular mechanisms, or applications in tissue engineering and regenerative medicine [6, 7].

More recently, there has been a large focus on protein crystal growth (PCG) in microgravity, which allows crystal structures to be grown uniquely larger and of higher quality than in 1g [4]. Crystallization processes are often used to manufacture drugs (including small-molecule drugs and peptide therapeutics) into an administered form, providing benefits in manufacturing, drug delivery, and storage of drugs, including relaxed temperature requirements. However, the process is difficult to achieve for drugs that use proteins (or other larger ingredients) as the active pharmaceutical ingredient. The microgravity environment can be utilized to investigate key variables for crystallization, particularly for these more challenging ingredients, as microgravity provides reduced sedimentation and minimal convection currents (temperature gradients) which can assist in the development of higher quality and more uniform crystals than those grown on Earth. These ideal conditions, once determined in microgravity, can then be replicated on Earth [7, 8].

Another notable topic of interest is nanofluidics, which can be applied to drug delivery techniques or fluidics-based diagnostics. Gravity has a large impact on the behavior of fluids, and microgravity has provided an intriguing environment for further study of fluidics. Recent experiments on the ISSNL have provided insight into our understanding of fluidics, particularly on the nano-scale, which have applications in biotechnology and medical devices [4, 6].
2.3 Technologies to Enable Human Spaceflight

The remote and autonomous nature of the ISS also prompts the development of improved medical devices to ensure the safety of crew members. Improvements include portability, as physical constraints in the ISS and future spacecraft deter the use of bulky equipment. Additionally, the devices should be easy to use by crew members who may not have extensive medical training. These improved device qualities produce technologies that are often superior and more convenient than those on Earth, which have remained in bulky, more complex forms due to a lack of necessity for change. Additionally, advanced and innovative technology results from capabilities developed for spaceflight. For example, expertise in robotics and water purification technologies have been repeatedly used for the development of technologies on Earth [4].

2.4 Existing Partnerships and Collaborations for Human Spaceflight and Earth applications

Currently, NASA has over 2500 active agreements with domestic and international partners in public, private, and academic sectors [9]. While NASA collaborates with many international partners on human spaceflight activities (the ISS being the most notable example), this report will confine the scope to domestic collaborations and work within the ISSNL. The domestic partnerships can be generally grouped into four categories: 1) government entity (federal agency or entity, state/local government), 2) industry, 3) academia, and 4) non-profit organizations. An approximate breakdown of these categories is provided in Figure 1a below from the 2016 NASA Presidential Transition Binder [10]. Figure 1b demonstrates a plurality of the partnership portfolio being dominated by federal agencies, such as the Department of Defense, Department of Commerce/NOAA, the Department of Transportation/FAA, and the Department of Energy [10]. NASA engages with external federal agencies through mechanisms such as Inter-Agency Agreements (IAAs).

Following the NASA Partnerships Guide [11], NASA is able to enter into the following types of agreements with external entities: federal procurement contract [12], grant or cooperative agreement, reimbursable Space Act Agreements (SAAs), non-reimbursable SAAs, funded agreements SAAs, equipment loans, real property-out grants, and commercialization of NASA technology. The type of partnership is also meant to inform the definition of partner roles, individual and mutual objectives, communication mechanisms, and determination of the exchange of goods/services (and funds if applicable).
A critical NASA partnership that will be highlighted in this report is the cooperative agreement with the Center for the Advancement of Science in Space (CASIS) which is a non-profit, non-government organization that has managed the ISSNL since 2011. In 2019, an external review of the ISSNL was performed to assess organizational structure, efficiency, and effectiveness of the ISSNL and the CASIS-NASA partnership [13], and the relevant findings of the review are referenced in this report.

3. Analysis

3.1 Human spaceflight research with potential Earth applications

Outcomes of human spaceflight and life science research in microgravity were reviewed to identify benefits to human health. The 2018 International Space Station (ISS) Benefits for Humanity document [4] was used as the primary source, along with various secondary sources. Relevant information was extracted from these documents to compile groups of technologies, knowledge, and products originating from human spaceflight which have the potential to influence human health on Earth. Items were assessed by metrics of potential economic, scientific, and social impact, and six categories of high impact to human health were identified (Fig. 2). Each category served as an organization method to identify trends seen in different types of technologies and to determine if different strategies for development are more suited to certain technology types. Strategies for development include 1) development and procurement methods, 2) types of partnerships or collaborations (public, private, commercial, academic), and 3) routes to commercialization. High-level observations point to which categories have been most successful at generating benefit, and which have yet to meet their full potential. It should be noted that due to the fairly recent timeframe of ISS research and the rigorous approval mechanisms required for pharmaceuticals and medical devices, many outcomes and potential benefits have yet to reach fruition. It should also be noted that outcomes considered in this work provided a far from exhaustive list of technologies with benefits to human health. For the purposes of this analysis, a snapshot of outcomes, primarily derived from the ISS Benefits for Humanity document, was used to identify some of the most notable examples of success and observe general trends.

![Figure 2. Six identified categories of high impact on terrestrial human health derived from spaceflight activities](image-url)
3.1.1 Pharmaceuticals and Biotechnology

The pharmaceuticals and biotechnology category largely encompasses life sciences research in microgravity. This differs from many of the remaining categories, which include technologies derived from the necessities of spaceflight. Life sciences research rather exploits the presence of humanity in space. Pharmaceuticals and biotechnology research in microgravity has allowed for the development of new and improved pharmaceutical therapeutics and drug delivery techniques. As of 2018, over 30% of journal publications resulting from ISS research were related to biology and biotechnology, exemplifying high scientific impact [4]. Highlights of drugs derived from US spaceflight activity are outlined in Table 1. Beyond the US-based efforts outlined in Table 1, the Japan Aerospace Exploration Agency (JAXA) is also exploring protein crystals, notably including a drug for Duchenne’s muscular dystrophy (DMD) that has now completed phase two clinical trials [4, 14].

### Table 1. Selected pharmaceuticals and biotechnology derived from US spaceflight activities

<table>
<thead>
<tr>
<th>Description</th>
<th>Route to Development</th>
<th>Valuation &amp; Outcome</th>
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<tr>
<td>Amgen, Inc.: Denosumab (brand name Prolia), a bone antiresorptive drug</td>
<td>Amgen partnered with BioServe (UC Boulder) for a space shuttle flight in 2001 using on-board equipment (Commercial Biomedical Testing Module).</td>
<td>Prolia became available on the market in 2010. It has since reached an annual revenue of $2.7 billion in 2019, and now has the third-highest revenue of Amgen’s products. More than 850,000 active patients were reported in 2017. At least 2 publications resulted from the microgravity experiments, with additional publications from ground-based work [4, 5].</td>
</tr>
<tr>
<td>Merck Sharp &amp; Dohme Corp.: Subcutaneous delivery of pembrolizumab (brand name Keytruda)</td>
<td>Merck performed this research through the ISSNL on a 1-month flight in 2017.</td>
<td>Microgravity experiments were successful in producing a crystalline suspension suitable for injection and results were published in the Nature Partner Journal: Microgravity in 2019. Phase 1 Clinical trials of the subcutaneous version are currently in progress [8, 15, 16].</td>
</tr>
<tr>
<td>Gilead Sciences, Inc: Implant for delivery of pre-exposure prophylaxis drugs for HIV</td>
<td>Houston Methodist Research Institute (HMRI) performed nanofluidics experiments on the ISSNL which led to a partnership with Gilead and a 2016 NIH grant to develop an implant for HIV.</td>
<td>The implant was successfully developed. It appears that the implant may be undergoing approval processes. Multiple publications have resulted from this work [4].</td>
</tr>
</tbody>
</table>

3.1.2 Improved Medical Devices and Techniques

Capabilities developed to maintain astronaut health and translatable technologies from spaceflight have contributed to new products and techniques for medical applications on Earth. This category primarily discusses products that are targeted towards healthcare providers. Based on the ISS Benefits for humanity document, most notable medical devices and techniques were derived from the work of international space agencies, with few examples from the US. Some examples of US medical devices (which also provide technologies for remote locations) are provided in Table 2, including an example of technology transfer licensing.

Of the examples from international space agencies, routes to development include 1) technology transfer or 2) partnerships between the space agency and a company or research organization [4]. There may be lessons learned from the successes in non-US space agencies; however, it is likely that some development routes may not be entirely applicable for recommendations to NASA and the US. The level of relevance in routes of development performed by non-US space agencies should be investigated. Nonetheless, the impacts and
Notably, the airway monitoring systems, NIOX MINO and NIOX VERO, from ESA-sponsored research, earned revenues of $18.4 million in the first 6 months of 2017. As of 2017, the device was used to perform 3.6 million tests annually. Between 2004 and 2014, the Chronos Eye-Tracking Device (C-ETD), also from ESA-sponsored research, earned $15 million in revenue and has been used in 30 to 40 leading laboratories for vestibular research and neurology [4]. Canada’s expertise in robotics, primarily through MacDonald, Dettwiler and Associates (MDA), produced the CanadaArm and led to a variety of surgery robotics, including the Neuromark, Bright Matter Drive, and Image Guided Autonomous Robot (IGAR) device. Over 35 publications have resulted from this work. The neuroarm and its successor, SYMBIS, has been successfully used in over 70 surgical cases. Additionally, the IGAR device has completed phase I and phase II clinical trials for use in robotic breast biopsy [4].

The lack of medical devices from US spaceflight activities represented in the ISS Benefits for Humanity document may potentially indicate an insufficiency in NASA’s efforts to provide routes for such technologies to reach their full potential on Earth. While NASA Spinoff documentation does note a wide variety of medical devices, the outcomes and impact of medical devices derived from US spaceflight activities should be further investigated and compared to the successes of non-US space agencies.

### 3.1.3 Technologies for Tele-Health and Remote Locations

Devices and technology developed for space are often highly suited for remote locations or developing countries on Earth, where medical technology may be limited by power infrastructure, lack of expertise, or distance to the nearest medical facility. This suggests that technologies for human spaceflight may have a high potential social impact value through benefits to global health. There are two technologies with concrete examples of Earth benefit: water purification technologies and ultrasound (Table 2) [4]. As demonstrated by the WINFOCUS ultrasound training, NASA expertise can contribute to techniques and training methods [4]. In addition to these examples, robotics for telemedicine and fluidics-based diagnostics for infectious diseases were pursued through NASA’s academic collaborations [4]. While less related to human spaceflight, Earth imaging can also be used to detect and monitor environmental factors related to infectious diseases and global/public health [17].

<table>
<thead>
<tr>
<th>Description</th>
<th>Route to Development</th>
<th>Valuation &amp; Outcome</th>
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<tr>
<td>Aquaporin-Inside Tap Water</td>
<td>NASA supported Aquaporin’s technology development through NASA’s Next Generation Life Support project in 2010. NASA then oversaw ESA-sponsored ISS experiments.</td>
<td>Aquaporin’s highly innovative water purification technology is now available on the market, with a revenue of $7.9 Million in 2018, tripling since 2017. The company has goals to apply their technology in developing countries, but it appears this work is still in development as the company matures [4, 18].</td>
</tr>
<tr>
<td>Reverse Osmosis technology</td>
<td>A familial connection with a NASA employee allowed NASA technology to be utilized for water purification in remote locations through the WSC.</td>
<td>WSC has established 800 village water processing systems in Mexico, Central, and South America, in addition to water bottle filling stations, home water purifiers, and first response devices which have been distributed in other countries [4]. Economic value is not</td>
</tr>
</tbody>
</table>
mWater is a non-profit venture with an open-access business model founded by a former NASA employee using NASA technology. mWater provides low-cost water quality tests and mobile monitoring software, which receives 120,000 submissions per month from 158 countries. The mWater app is used by more than 40,000 organizations including non-governmental organizations (including USAID, UNICEF, WHO, and the World Bank Innovation Fund), governments, and researchers [4].

Sonomotion’s Flexible Ultrasound System (FUS) ZIN Technologies worked with GE to modify the GE Vivid-E95 clinical ultrasound device to create a device for NASA. It appears that the University of Washington was also a collaborator in this effort. The technology was later licensed in 2015 to Sonomotion from the University of Washington. Over 40 publications and patents resulted from the development of this technology. Since licensing the technology, Sonomotion has received grant funding from the NIH, NASA, and NSBRI. Clinical trials are currently in progress for their BreakWave(TM) system [4, 19, 20].

World Interactive Network Focused on Critical Ultrasound (WINFOCUS), Ultrasound Training NASA’s Advanced Diagnostic Ultrasound in Microgravity (ADUM) project collaborated with WINFOCUS to apply ADUM training procedures on Earth. It appears that the ADUM principal investigator (an M.D. at the Henry Ford Hospital) personally pursued the connection with WINFOCUS. Over 20,000 people in 68 countries have been trained using ADUM methods. The American College of Surgeons now uses the ADUM program for ultrasound training, bringing the technology to medical school curriculums. [4, 21]

### 3.1.4 Advanced Assistive Devices

Assistive device technologies have been developed through astronaut countermeasures or translatable technologies from spaceflight. Robotics expertise from U.S. spaceflight technologies has been applied to exoskeletons with applications on Earth; although, these technologies appear to be in development (not yet on the market). This includes an academic collaboration to develop the X1 Robotic Exoskeleton [4]. Additionally, NASA co-developed Robonaut with General Motors (GM) through a Space Act Agreement. This technology was licensed to BioServo to develop a RoboGlove, and GM is highly interested in the development of this product for use in their manufacturing plants [4].

Numerous examples of advanced assistive devices have also resulted from the work of non-US space agencies. This includes Russia’s Adeli Suit therapy for children with cerebral palsy and ESA’s augmented reality glasses for communication [4]. These technologies primarily result from countermeasure developments for astronauts, rather the more general expertise utilized in the US-based examples.

### 3.1.5 Improved Understanding of Human Physiology

The study of the human body in space has revealed new knowledge that can be applied on Earth. High scientific value has been achieved, as over 20% of all ISS peer-reviewed journal publications and over 15% of conference papers between 1998 and 2018 were related to human research [4]. Work in this area leverages internal NASA work, academic collaborations, and in some cases commercial collaborations.

Related areas of research include multiple physiological systems. Bone loss research is applicable to conditions associated with bone loss on Earth, including amputation, lower-leg fractures, and ligament tears. Human spaceflight research can also indicate the usefulness of pharmaceutical and nutritional countermeasures for bone and muscle loss conditions [22]. Studying the cardiovascular and respiratory systems in microgravity has
led to a greater understanding of the changes caused by different body postures on Earth [22]. Work in the neurovestibular system can provide information about humans’ neural plasticity [22]. Additionally, the space environment can serve as a model for aging, due to many of the adaptations that it causes [4].

Beyond the direct development and testing of pharmaceuticals in microgravity (discussed in section 3.1.1), omics research investigating biological responses in the space environment can yield information about physiological mechanisms and biological pathways that can later be leveraged in the development of therapeutic interventions on Earth [7]. Creative approaches for sharing findings from space research have been developed, including NASA’s Gene Lab which provides an open-access repository of omics studies from ISS research, allowing academic and commercial organizations to use NASA’s findings and raw data for Earth applications [7].

3.1.6 Translatable Technology and Expertise for Emergency Response

NASA’s capabilities and technologies have also had direct technology, knowledge, and resource transfer to aiding individuals and teams in emergency response situations. For example, various spinoff technologies have been developed for the first responder communities, such as improved polymer textiles for firefighting gear [23], emergency medical services communication systems [24], and ambulance decontamination and atmosphere characterization [25]. The current COVID-19 pandemic has highlighted the capacity of many aerospace entities, including NASA, to redirect technical resources to address medical equipment supply shortages. NASA’s Jet Propulsion Lab and Armstrong Flight Research Center have teamed with surrounding aerospace companies in Southern California to distribute engineering expertise and manufacturing equipment toward producing personal protective equipment (such as masks and face shields) and medical devices (ventilators) [26]. While the re-direction of resources and capabilities is unique to the pandemic, NASA has documented various examples of spinoff technology work on ventilators dating back to 2011 [27], demonstrating that the translatable expertise and resources have been implemented through both direct and indirect technology and knowledge transfer mechanisms.

3.2 Partnerships and Collaborations to Promote Earth Application of Human Spaceflight Research

In this report, examples of partnerships between NASA or the ISSNL and external entities were examined based on their relevant working groups, mechanisms used to facilitate collaboration, and joint research topics. This section only highlights a handful of collaborations within each partnership type and is naturally not an exhaustive list. Of NASA’s domestic partnerships, 1142 active SAAs with commercial, local state government, and non-profit partners are publicly listed by the NASA Partnerships Office [28]. An initial keyword search was performed on this set of partnerships specifically, and approximately 20 agreements focused on human health and performance or life science topics. Search results were excluded from the count if the topic was not relevant to work or research on human systems.

<table>
<thead>
<tr>
<th>Keyword</th>
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<tr>
<td>Human</td>
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<td>Life support</td>
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<td>Medical</td>
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3.2.1 Government Collaborations

NASA interacts with federal departments and agencies through the NASA Office of International and Interagency Relations (OIIR). NASA may also partner with state and local governments through a variety of mechanisms such as interagency agreements, as well as with national academies or organizations through joint working or discussion groups. A brief overview of examples are highlighted in Table 3 below.

<table>
<thead>
<tr>
<th>Partner Type</th>
<th>Partner Examples</th>
<th>Relevant Group(s) within Collaborating Entity</th>
<th>Collaboration Mechanism(s) with NASA</th>
<th>Joint Human Research or Activity Area(s)</th>
</tr>
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<tbody>
<tr>
<td>Government Agency</td>
<td>Department of Defense (DoD)</td>
<td>• US Army Medical Research and Materiel Command</td>
<td>• Interagency Agreement</td>
<td>• Pharmaceuticals and Biotechnology</td>
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<td>• Army Research Office: Human Research and Engineering Directorate [4]</td>
<td>• Federal procurement contract</td>
<td>• Medical Devices</td>
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<td>• Air Force Office of Scientific Research: Human Performance and Biosystems [5]</td>
<td>• Jointly funded and/or managed programs (Cooperative Agreement, Non- or Reimbursable SAA)</td>
<td>• Assistive Devices</td>
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<td>• Real property-out grants</td>
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<td>• Discussion forums/groups</td>
<td>• Medical Operations</td>
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<td>Department of Health and Human Services (HHS) [30] [31]</td>
<td>• National Institutes of Health (NIH)</td>
<td>• Interagency Agreement</td>
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<td>• Food and Drug Administration (FDA)</td>
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<td>• Centers for Disease Control (CDC)</td>
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<td>• Scientific Potential/Actual Collaborative Efforts (SPACE) group</td>
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<td>National Science Foundation (NSF)</td>
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<td>• Social, Behavioral and Economic Sciences Directorate</td>
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<td>Federal or National Entity</td>
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<td>• Published literature</td>
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### 3.2.2 Industry Collaborations

The 2018 ISS Benefits for Humanity documents notes 16 ISS commercial research providers, which offer facilities or equipment for onboard research. This includes facilities from companies such as NanoRacks, Made in Space, and Bioserve. Three of the listed commercial research providers were implemented in 2018, showing the recent acceleration of these capabilities [4]. Table 5 highlights a few examples of NASA industry relations and partnerships conducting human health research activities.

<table>
<thead>
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<th>Table 5: Examples of industry collaborators in human health research</th>
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<td><strong>Partner Type</strong></td>
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<td>Large businesses</td>
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<td>Small businesses</td>
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### 3.2.3 CASIS Collaboration and ISS Research Commercialization Opportunities

The ISSNL provides a unique platform to conduct microgravity research for researchers in all four groups of partnerships: government, industry, academic, and non-profit. This environment is particularly valuable to pharmaceuticals and biotechnology companies, and commercial companies have demonstrated strong interest in accessing the microgravity environment, with 56% of ISSNL experiments sponsored by commercial entities between 2012 and 2017 [4]. A strong draw for commercial researchers is the 50% allocation of NASA’s ISS resources to conduct research for these external entities [4]. In turn, the growing interest and demand has benefitted other interested entities by lowering cost of access to orbit for entities such as academia (which made up ~42% of the ISSNL portfolio in the 2012-2017 period). Interestingly, government sponsored projects (external to NASA) only comprised 2% of the portfolio [4] even though government partners dominate the overall NASA partnerships catalog.

CASIS has been in a cooperative agreement with NASA to manage the ISSNL since 2011. An independent review of the partnership and business infrastructure was conducted in 2019 to examine the efficacy of this relationship to meet NASA and ISSNL objectives. Key observations and recommendations highlighted the need to clarify the partner roles in management and operations, especially given the overlapping domains between CASIS and
NASA’s Division of Space Life and Physical Sciences Research and Applications (SLPSRA) within the Human Exploration and Operations Mission Directorate (HEOMD). While knowledge and technology transfer is inherently generated and beneficial for partners with similar research objectives, the dynamic created from partners with shared domains can create confusion about objectives and delineation of roles and is an important facet to consider when governmental agencies or entities with directed mandates or objectives seek to form partnerships.

4. Discussion

4.1 Human spaceflight research priorities with potential Earth applications

Based on the analysis of the six identified categories, clear patterns were seen which distinguish life sciences research (pharmaceuticals and biotechnology) from technology resulting from the development of capabilities for spaceflight (e.g. medical devices). Most success in pharmaceuticals and biotechnology is from projects through the ISSNL (or international partners), which have allowed commercial or academic entities to perform research in microgravity. As such, it is clear that the ISSNL, or a similarly enabled organization, is highly beneficial to the success of life sciences research in microgravity and its effect on terrestrial human health. Based on these findings, the following recommendations were made regarding ISSNL project selection:

**Recommendation:** When selecting projects, organizations like the ISSNL should consider potential Earth benefits (in all three categories of valuation) in its selection criteria.

**Recommendation:** When selecting projects, organizations like the ISSNL should ensure that human health topics are represented in the portfolio of accepted projects.

Further, the human health topics can be guided by previous successes. This includes three key life sciences technologies that were identified: PCGs, bone/muscle maintenance drugs, and drug delivery mechanisms [4,6]. However, selection criteria should additionally leave space for innovation.

**Recommendation:** When selecting projects, organizations like the ISSNL should consider previous successes in earth benefits to prioritize categories of research with promising outcomes

**Recommendation:** When selecting projects, organizations like the ISSNL should allow new, innovative or unconventional topics when appropriate

While these recommendations are derived from a human health lens, the list of recommendations would be incomplete without allowing for other disciplines and applications.

**Recommendation:** When selecting projects, organizations like the ISSNL should ensure that a breadth of disciplines is represented in the portfolio of accepted projects.

In addition, recommendations for selection criteria can be informed by a recent Independent Review of the ISSNL [13].

**Recommendation:** The project selection processes for life sciences projects should be clearly defined.
In addition to project selection, the facilities and resources of the ISSNL should be leveraged to promote commercial research and fulfill the needs of their experiments, as suggested by Reichert et al. [8].

**Recommendation:** ISS efficiency should be maximized and should continue to allocate a set percentage of resources (equipment and crewmember time) for private/commercial research, as is currently done through the ISSNL.

**Recommendation:** Laboratory areas and equipment dedicated to life sciences experiments should be considered, in order to continue to allow this type of research and overcome the challenges of performing experiments in microgravity.

Additionally, commercial access to space should be supported to fulfill the needs of experiments and maintain and improve the feasibility of microgravity research.

**Recommendation:** The ISSNL and commercial facilities/instruments should be leveraged to provide space access to private-sector research to pursue pharmaceuticals, etc.

**Recommendation:** Increased space access and decreased cost-to-orbit should be promoted to increase the accessibility of microgravity to pharmaceutical companies.

Considering technology developments for enabling spaceflight, routes for development primarily include either 1) technology transfer or 2) collaborations with commercial or academic entities. Regardless of development routes,

**Recommendation:** Potential Earth benefits (in the six identified categories or otherwise) should be identified during NASA’s internal development or procurement or technologies for human spaceflight.

As a broad recommendation, careful consideration and identification of potential benefits could improve the ability to prepare and strategize for the implementation of these Earth benefits. Trends observed in technology development show that many technologies that were successfully translated to Earth applications were developed with external partners, and these external partners typically initiated Earth application. Thus, strategies to promote implementation include the following:

**Recommendations:** Where possible, external partners (government, private/commercial, academic) should be considered for the development of necessary capabilities for human spaceflight.

**Recommendation:** Journal and conference publications should be pursued wherever possible, to promote scientific benefits.

**Recommendations:** Creative approaches for encouraging and maximizing Earth benefits should be pursued through mechanisms such as NASA’s Technology Transfer Program.

Considering different categories, medical devices and techniques, technologies for remote locations, and assistive devices, show similar trends in routes of implementation, beyond differences in targeted markets.
However, some unconventional routes to implementation are seen in technologies for remote locations. For example, personal connections with NASA were used in three successful global health initiatives. While these routes were beneficial, conventional routes should also be promoted to allow wider availability of NASA technology. Additionally, global health technologies show high social impact values but do not always have immediate economic success, which may hinder development.

**Recommendation:** NASA should pursue connections with non-profit organizations or global health start-ups which may help to facilitate earth applications.

This may include technology transfer from NASA or NASA funding to develop technologies for dual space and earth applications, perhaps through NASA’s Small Business Innovation Research (SBIR) program. The influence of NASA funding is documented by NASA’s work with Aquaporin: “NASA’s patronage was especially important to developing forward osmosis membranes, which have a longer path to the mainstream market and therefore are less attractive to investors. ‘They’re not afraid to make the first move’” [29]. Similarly to innovative technologies, global health initiatives often struggle to attract investors. NASA could consider grant programs to support technologies for remote locations, starting with a more general recommendation to pursue connections with relevant entities.

For both life sciences research and technology development for spaceflight capabilities, methods of tracking outcomes are vital to assessing benefit and guiding decisions.

**Recommendation:** The economic, scientific, and social impact outcomes of NASA’s life sciences and human spaceflight work should be tracked to inform how future research is prioritized.

**Recommendation:** The economic, scientific, and social impact outcomes of life sciences and human spaceflight work performed by non-US space agencies should be tracked to identify promising technology transfer topics and mechanisms that may be unrealized in the US.

To promote the availability of NASA technology, routes for technology development should be made publicly available. Many examples of Earth applications are documented through news articles, NASA Spinoffs, or the ISS Benefits for Humanity document. However, the exact mechanism of development is often unmentioned. Providing clear and easily accessible documentation of technology transfer could help interested companies to follow the example of previous successes.

**Recommendation:** Earth applications of technology should be advertised by NASA in publicly available promotional materials, and the routes to Earth applications should be clearly documented to provide a model for potentially interested parties.

### 4.2 Potential Areas for Future Partnerships and Collaborations

Based on the ISSNL portfolio to date, the laboratory appears to be underutilized by other government entities outside of NASA (with only 2% of projects being government sponsored) [4]. This may be due to lack of awareness of capabilities enabled by the microgravity environment or lack of familiarity in designing for the environment. Additionally, all government agencies are tasked with specific directives and scope, which may generate political concern with entities attempting to share scope. Even though the ISSNL is deemed as a
national lab, its creation and management history, as well as the unique environment of operations, has resulted in a difference in management and operations compared to other US national laboratories.

To further develop the collaborations between federal agencies, it is valuable to continue leveraging NASA’s Partnerships Office, the Technology Transfer Office, the Office of International and Interagency Relations (OIIR), and the future ISSNL User Advisory Committees and also identify sister offices or human research divisions in external federal agencies that perform similar functions to [4]. Similarly for industry, these offices and other programs like the SBIR/STTR program, serve as important communication tools. For academia and non-profit organizations, SLPSRA, the Partnerships Office, and the Office of STEM Engagement could also help facilitate widely communicating open research announcements. Expanding calls for proposals to non-aerospace audiences (such as the medical community) and highlighting communication of current academic research partners based in non-aerospace domains will promote communication of human research capabilities in spaceflight environments. Ensuring routine documentation and publication of group discussion and recommendations will promote knowledge and technology transfer.

**Recommendations:** Create or continue public and accessible documentation of current or past partnerships in human health research for both Earth-based and ISSNL activities. Continue to track metrics on portfolio breakdown and representation by human health research, and track publication metrics for SLPSRA topic areas.

**Recommendations:** Continue to advertise and centralize documentation of NASA partnership engagement mechanisms, research areas, and examples of past partnerships. Communicate these mechanisms and research examples to non-aerospace, medical or human health forums, such as technical conferences, joint working groups, and national councils or committees.

Additionally, observing the relationship between CASIS and NASA highlights several lessons learned for more effectively building partnerships specifically to leverage the microgravity environment aboard the ISSNL. The scope and mission of each organization needs to be well defined to reduce the competition between organizations in competing for crew member hours and credit from research results. The flow of communications should also be clearly defined and will be influenced by the type of partnership agreement put in place. The review’s recommendation of establishing advisory and liaison roles from NASA will ensure that a consistent message is communicated to the partner organization. Creating user/partner advisory groups or feedback mechanisms, such as the ISSNL User Advisory Council [1], for research partners in government, industry, and academia can also provide insights on microgravity accessibility, barriers to research translation and development for spaceflight, and ISSNL resource demand. These insights should also be communicated to a wider audience of current and potential partners through the forums noted previously (Partnerships Office, OIIR, et al.) to educate about and remove barriers to access.

**Recommendations:** Delegate representatives from NASA HRP, other federal agencies, medical industry, academia, and non-profits to provide input to the new ISSNL User Advisory Committee on how ISSNL capabilities can be better accessed and managed

**Recommendations:** Ensure the scope and mission of each partner organization is well defined.

**Recommendations:** Ensure procedures for conducting research are developed to prevent competition in the use of crew hours and research credit.
**Recommendations:** Define routes for flow of communication between partners (advisory committees and liaison) and ensure that research objectives and outcomes are communicated upfront to prevent competing objectives.

**Recommendations:** Ensure the project selection processes for life sciences projects should be clearly defined.

### 4.3 Future Directions

There are several open questions that could be analyzed by future work. This work primarily focused on US domestic outcomes; however, we did note some differing outcomes in the work of international space agencies. The difference in the approaches of the US and international space agencies to translating earth applications should be investigated. Additionally, the ISS Benefits for Humanity document was used as a primary source for this analysis and shows fewer US spaceflight derived medical devices when compared to the successes of non-US space agencies. The outcomes of medical devices derived from US spaceflight activities should be further investigated with a rigorous analysis of additional sources, potentially using the NASA Spinoffs database.

Many reports of Earth benefits do not indicate the requirement of humans-in-the-loop in life sciences research in microgravity. This report has encompassed research that is tangential to human spaceflight (i.e. ISS and shuttle experiments). A deeper analysis should determine which life sciences topics require or benefit from a human presence in space, and which types of experiments could become self-sustainable. This would clarify the reliance of such research on human spaceflight versus the more general access to space.

Lastly, inter-agency collaborations within the US were analyzed through this report. However, outcomes of many of these partnerships are absent from most records of Earth benefits. The question remains if these collaborations have been less successful than commercial or academic partnerships, or if they are not well publicly documented. Even when investigating technology transfer and commercial or academic partnerships, documentation was often limited to NASA’s promotional materials which provided difficulty for rigorous analysis. Access to more detailed records would allow for a more reliable and robust set of information for future analysis and confirmation of the preliminary findings reported in this paper.

### 5. Policy Recommendations

#### 5.1 Recommendations for human spaceflight research priorities with potential Earth applications

- When selecting projects, organizations like the ISSNL should consider potential earth benefits (in all three categories of valuation) in its selection criteria
- When selecting projects, organizations like the ISSNL should ensure that human health topics are represented in the portfolio of accepted projects.
- When selecting projects, organizations like the ISSNL should consider previous successes in earth benefits to prioritize categories of research with promising outcomes.
- When selecting projects, organizations like the ISSNL should allow new, innovative, or unconventional topics when appropriate
- When selecting projects, organizations like the ISSNL should ensure that a breadth of disciplines is represented in the portfolio of accepted projects.
Potential earth benefits (in the six identified categories of high impact to human health and three categories of valuation) should be identified during the development or procurement technologies for human spaceflight.

- The economic, scientific, and social impact outcomes of NASA’s life sciences and human spaceflight work should be tracked, to inform how future research is prioritized.
- The economic, scientific, and social impact outcomes of life sciences and human spaceflight work performed by non-US space agencies should be tracked to identify promising technology transfer topics and mechanisms that may be unrealized in the US.

5.2 Recommendations for facilitating Earth applications of human spaceflight research

- Where possible, external partners (government, private/commercial, academic) should be considered for the development of necessary capabilities for human spaceflight.
- Journal and conference publications should be pursued wherever possible, to promote scientific benefits.
- Creative approaches for encouraging and maximizing earth benefits should be pursued, such as NASA’s technology transfer program.
- NASA should pursue connections with non-profit organizations or global health start-ups which may help to facilitate earth applications.
- Earth applications of technology should be advertised by NASA in publicly available promotional materials, and the routes to Earth applications should be clearly documented to provide a model for potentially interested parties.

5.3 Recommendations for potential commercialization opportunities with potential Earth applications

- ISS efficiency should be maximized and should continue to allocate a set percentage of resources (equipment and crewmember time) for private/commercial research, as is currently done through the ISSNL.
- Laboratory areas and equipment dedicated to life sciences experiments should be considered, in order to continue to allow this type of research and overcome the challenges of performing experiments in microgravity.
- The ISSNL and commercial facilities/instruments should be leveraged to provide space access to private-sector research to pursue pharmaceuticals, etc.
- Increased space access and decreased cost-to-orbit should be promoted to increase the accessibility of microgravity to pharmaceutical companies.

5.4 Recommendations for Ensuring the success of Partnerships and Collaborations

- Create or continue public and accessible documentation of current or past partnerships in human health research for both Earth-based and ISSNL activities
  - Continue to track metrics on portfolio breakdown and representation by human health research, and track publication metrics for SLPSRA topic areas.
- Continue to advertise and centralize documentation of NASA partnership engagement mechanisms, research areas, and examples of past partnerships.
Communicate these mechanisms and research examples to non-aerospace, medical or human health forums, such as technical conferences, joint working groups, and national councils or committees.

Delegate representatives from NASA HRP, other federal agencies, medical industry, academia, and non-profits to provide input to the new ISSNL User Advisory Committee on how ISSNL capabilities can be better accessed and managed.

Recommendations for improving the CASIS-NASA Partnership and informing future CASIS partnerships with government/industry/academic partners:

- Ensure the scope and mission of each organization should be well defined.
- Ensure procedures for conducting research are developed to prevent competition in the use of crew hours and research credit.
- Define routes for flow of communication between partners (advisory committees and liaison) and ensure that research objectives and outcomes are communicated upfront to prevent competing objectives.
- Ensure the project selection processes for life sciences projects should be clearly defined.

References:


A Preliminary Analysis of Key Upcoming Human Spaceflight Policy Questions

Seamus Lombardo
12/10/2019
16.423
Professor Dava Newman
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Appendix

A. Outreach presentation..................................................................................................17
1 - Statement of Purpose

Human spaceflight policy has undergone changes with each new presidential administration since the completion of the Apollo lunar landings. These changes have yielded tremendous accomplishments, such as the International Space Station (ISS), that have pushed the boundaries of science and engineering. However, costly program reversals that fell short of their goals have also occurred, such as the Constellation program. Considering this history, it is essential that the human spaceflight policy of the incoming administration be carefully considered to maximize the successes and benefits that result from the nation’s large investments in human spaceflight. Key human spaceflight policy questions will guide NASA’s efforts over the next decade. This report seeks to address key issues: NASA’s role in the future of the International Space Station, NASA’s plans for future deep space human exploration and the role of international and private partners in future human spaceflight missions. This work first provides a brief review of the historical and current American human spaceflight policy. A summary of the state of the other major nations and commercial entities in human spaceflight is also be provided. Past literature is then examined with respect to the key objectives and benefits of human spaceflight programs. With this foundation established, the current state of U.S. human spaceflight policy with respect to each of the key areas above is examined, policy directions are compared, and recommendations are provided after analysis utilizing the aforementioned objectives and benefits of human spaceflight.

2 - Literature Review

2.1 - Overview of Past of U.S. Space Policy

NASA was established via the National Aeronautics of Space Act of 1958 [1]. This established NASA as a civilian space agency and was prompted in part due to the Soviet Union’s launch of the Sputnik satellite the previous year [2]. The sentiment of reasserting American leadership in space through the creation of NASA is stated in the act itself when the document calls for, “preservation of the role of the United States as a leader in aeronautical and space science and technology” making it clear that NASA’s creation was in large part driven by the political situation of the Cold War.

Motivations of American dominance in space were furthered by President Kennedy’s proposal to land astronauts on the moon [3]. Conversations between President Kennedy at NASA Administrator James Webb show that Kennedy’s primary reason for supporting NASA was to beat the Soviets and that he was not personally interested in space exploration [4]. After his death, the human spaceflight program continued in this initial direction based on pride and prestige. This era of U.S. space policy was characterized by a national focus on these human spaceflight missions and during this time NASA received the highest funding levels in its history, hitting a peak of over $30 billion in 2019 dollars [5].

However, after the completion of the Apollo landings in the 1970s human spaceflight began to decrease in stature as a national priority and there were concerns about the costs of the spaceflight program [6]. To determine the post-Apollo direction of human spaceflight, President Nixon created the Space Task Group to examine various options. The conclusions of this report were driven by a desire for human spaceflight missions that were more affordable and increased reusability. While the report produced several recommendations including a space station and an eventual mission to Mars, the main suggestion that was acted upon was the creation of the Space Shuttle program [7].

The next major stage in the U.S. human spaceflight program came with the development of the International Space Station. The program was announced by President Regan as space station Freedom and gained partnerships from Canada, Europe and Japan in 1988. Under the Clinton administration these partnerships were expanded to include Russia [8]. While the ISS experienced many schedule delays and cost overruns, it has served as a model for international collaboration; constructed by 15 international partners, hosting astronauts from 18 countries [9] and scientific investigations involving 83 countries [10].
There have also been several attempts by policy makers to return to the Moon. President George H.W. Bush proposed on such plan in his space policy address in 1989 [8] and this was followed by the Constellation program proposed by George W. Bush in 2005. The Constellation program involved developing new launch vehicles and spacecraft for both the ISS and a return to the lunar surface but was plagued by scheduling and budgetary issues before being cancelled by the Obama administration under the guidance of the Augustine Commission [11]. The history of U.S. human spaceflight policy can be characterized by successful missions both to the moon and in low earth orbit (LEO), but also by cost and scheduling issues and reversals of direction. The objectives and rationales of human spaceflight have also evolved over the course of NASA’s history, as will be elaborated upon in a following section of this report.

2.2 - Current Human Spaceflight Policy

In 2010, the Obama administration issued the National Space Policy [12] which set out high level priorities such as international collaboration and increased public-private partnerships that guide human spaceflight policy direction. The policy also contains several specific directions regarding human spaceflight including the continued operation of the ISS through 2020 and beyond, private partnerships for the transportation of crew to the ISS, a crewed mission to an asteroid in the mid-2020s and a human mission to Mars in the 2030s. In 2017, the Trump administration amended a portion of this policy to eliminate the mission to an asteroid and replace it with a “return of humans to the Moon for long term exploration and utilization” [13] however, the rest of the policy has remained intact.

2.3 - Foreign Human Spaceflight Programs

As other nations have a key role in all the questions addressed in this document, it is important provide a brief background on the history of current state of these human spaceflight programs.

2.3.1 - Russia - Russia (formerly the USSR) has an extensive heritage of human spaceflight, including putting the first human in space. While the programs of the US and USSR began as rivals, they have since had a long history of collaboration in human spaceflight (including the Apollo-Soyuz docking and Shuttle-Mir program) that carries through to present-day cooperation on the ISS. Today Russia maintains its own independent access to human spaceflight, and since NASA’s retirement of the Space Shuttle in 2011, has also carried American astronauts to the space station aboard the Soyuz spacecraft [14].

The Russian space effort is currently run by Roscosmos, which unlike NASA’s purely civilian mission, plays a role in both civil and military space efforts. Another key difference between NASA and Roscosmos is their funding levels. Roscosmos had a $2.16 billion budget in 2018 (compared to a $20.817 billion budget for NASA) which was decreased from a $5 billion budget in 2014 due to a drop oil prices and sanctions placed on Russia by the West [15]. Despite these budgetary issues, Russia still deems it valuable to invest in manned spaceflight due to the geopolitical importance of this international collaboration [16]. Russian space policy also shows that preserving the nation’s role as a leader in the field of human spaceflight is an important objective of the program, as evidenced government guidelines [17].

2.3.2 - China - Alongside the US and Russia, China is the only other nation to develop the independent capacity for human spaceflight. China sent its first Taikonaut into orbit in 2003 and since then has developed two temporary space stations, Tiangong-1 and Tiangong-2. China also has ambitious plans for its human spaceflight program including a permanently crewed space station and the eventual goal of a lunar base [18]. Like Russia, the Chinese space military and space efforts are combined, with its human spaceflight program falling under the People’s Liberation Army. Though China’s space budget is not publicly disclosed, it has been estimated at $8 billion, placing it ahead of Russia but behind the US [19]. China’s motivations for its human spaceflight program are numerous and include economic development, national prestige and soft power projection [20].

Another key objective of China’s human spaceflight program is international collaboration and diplomacy. This is evidenced by China’s announcement that international collaborators will be allowed to conduct scientific research on its planned permanent space station [18]. However, unlike most nations that
participate in human spaceflight, China does not collaborate on the ISS. This is due to restrictions the U.S. has placed on collaboration with China in the space sector, which will be elaborated upon in a following section of this report.

2.3.4 - The European Space Agency (ESA) - ESA (an international collaboration of 22 member states) does not have the independent ability to send humans to space. Nonetheless, ESA still has a significant human spaceflight heritage, participating in the Space Lab missions with NASA and launching its first astronaut aboard the space shuttle in 1983 [21]. Additionally, ESA was one of the initial partners in the ISS and contributed its own Columbus module [8]. Currently, ESA has a budget of $6.3 billion, 12% of which goes towards human spaceflight activities [22]. ESA also maintains its own astronaut corps [23] and is collaborating with the US on exploration systems such as the Orion European Service Module [24].

2.3.5 - Japan - Like ESA, the Japanese Aerospace Exploration Agency (JAXA) has no independent human spaceflight capabilities. However, it too has a history of significant involvement in human spaceflight, as demonstrated by its astronaut corps and its contributions to the ISS through its Kibo module [17]. Additionally, JAXA has developed the HTV transfer vehicle to resupply the ISS. Of JAXA’s $1.7 Billion budget a significant portion is spent on its involvement in the ISS [25]. Going forward, JAXA has expressed interest in collaborating with NASA on future deep space exploration plans and is also supportive of the Trump’s administrations efforts to increase commercial activity on the ISS [26].

2.3.6 - India - Although India has not yet sent any humans to space independently, it has a successful space program in many other respects. It has developed its own launch vehicles and interplanetary exploration missions [27]. However, it is important to include the Indian Space Research Organization (ISRO) in the discussion of the future of human space exploration, as they have ambitious plans in this area. These plans involve developing a spacecraft to carry a crew to LEO aboard an Indian launch vehicle and technology assessment has begun towards this goal. These human spaceflight plans are estimated to cost $1.4 billion and would entail a significant portion of ISRO’s current $4 billion budget [28]. While India has yet to decide on whether to follow through with these proposed plans for a human spaceflight program, ISRO will likely continue to play a significant role in the global spaceflight ecosystem.

2.3.7 - Other Human Spaceflight Programs - Many other countries have participated in human spaceflight efforts. One such example is the Canadian Space Agency, which maintains its own astronaut corps and has also made significant contributions to the ISS such as the station’s robotic arm [29]. Additionally, countries from all over the world including Brazil, South Africa, South Korea, and Malaysia have sent astronauts to the ISS through collaboration with other nations. The group of nations that have invested resources in sending humans to space continues to expand, exemplified by Hazzaa Ali Almansoori, the first astronaut from the United Arab Emirates who flew to the ISS in 2019 [30].

2.4 - Commercial Entities in Human Spaceflight - Private companies have always played a role in human spaceflight in the US, as exemplified by the many private contractors (such as Boeing and Lockheed Martin) on projects such as Orion and the ISS [31]. However, over the past decade commercial spaceflight companies have expanded their work into public-private partnerships with NASA where these partners provide a cargo or crew transport to the ISS as well as independent suborbital space tourism ventures. One major example of public-private partnerships is the ongoing commercial resupply services contracts for the ISS. SpaceX and Orbital ATK first developed the necessary rockets and spacecraft under the initial Commercial Orbital Transportation Services program, before being award contracts to continue supplying the ISS [32]. Under these contracts, these private companies have successfully provided supplies to the space station over dozens of flights. Under the commercial crew program, NASA has also been collaborating with SpaceX and Boeing to develop spacecraft to transport astronauts to the ISS. While these vehicles have not yet successfully transported crew to the station, SpaceX has successfully flown their Crew Dragon spacecraft to the ISS and Boeing is scheduled to do the same with their Starliner Spacecraft in late 2019 [33]. Beyond the ISS, NASA is also seeking to utilize private public partnerships to resupply the
planned Lunar Gateway (a planned orbital platform for human exploration of the moon) [34] and transport cargo and scientific payloads to the lunar surface [35].

In addition to these partnerships with NASA, commercial entities are also investing in their own independent human spaceflight efforts. Blue Origin and Virgin Galactic have developed spacecraft and launch vehicles that are anticipated to take their first tourists on suborbital spaceflights in 2020 and have plans to use these vehicles to perform microgravity research [36, 37].

2.5 - Objectives for Human Spaceflight - To analyze policy options for human spaceflight, it is important to consider its objectives. The goals of human spaceflight have changed substantially since its beginnings. During the Apollo era, human spaceflight was primarily motivated by the Cold War between the US and USSR. However, since the conclusion of the Apollo program and the decline in accompanying record levels of NASA funding, the objectives and rationales for human spaceflight have been examined more critically as they have had to find their place among other national priorities [17].

The objectives of human spaceflight range from the search for extra-terrestrial life to human settlement of the solar system. The 2018 Global Exploration Roadmap, a collaborative document between the world’s major space agencies [38], lays out objectives of human space exploration including: expanding humanity’s presence in solar system, understanding the universe, engaging the public, stimulating economic prosperity, and fostering international cooperation. While these objectives doubtlessly include goals for human exploration and benefits that can be derived from these efforts, it is also important to examine literature that critically evaluates which of these objectives are most effectively accomplished through human spaceflight specifically. A 2009 document by Mindell, Uebelhart, Siddiqi and Gerovitch classified similar goals into primary and secondary objectives. Primary objectives are defined as those that can only be accomplished effectively by sending humans to space and where the benefits exceed the inherent risks and high costs associated with human spaceflight. These include exploration, national pride, and international prestige and leadership. Secondary objectives such as science, new technologies, economic development, and education are benefits that result from human spaceflight but could be accomplished via other means or do not completely justify the cost of human spaceflight. In making their case for this organization of objectives, Mindell et al. cite the fact that while human spaceflight doubtlessly yields scientific insight, a human mission to Mars would cost many times the annual budget of the National Science Foundation, which is explicitly responsible for basic science research in the US. This stands in contrast to the exploration aspect of the Apollo landings, which the authors argue expanded the human experience through a moral and cultural dimension in a way that a robotic mission would be incapable of doing. The authors also regard human spaceflight missions such as Apollo as instruments for projecting soft power and cultivating international prestige in a way that other efforts could not. A recent speech by Vice President Mike Pence demonstrated that the objectives of international prestige are still objectives of the human spaceflight program [39].

Similarly, a 2014 report by the National Academies [40] classified the goals of human spaceflight into pragmatic goals, which the committee argues could be accomplished by either robotic or human exploration, and aspirational goals, which are accomplished by human spaceflight specifically. The pragmatic goals include: economic and technological development, national security, international relations, science, and education while the aspirational goals were related to human survival through expansion into the solar system and a shared human aspiration for exploration. When examining the current National Space Policy, many of these goals are mentioned, as well as the explicit goal of public-private partnerships. For the analysis of the questions in this work, we have elected to utilize the same categories of objectives as Mindell et al, with some adjustments to their content as shown in Table 1.
### Table 1: Objectives of Human Spaceflight

<table>
<thead>
<tr>
<th>Primary Objectives</th>
<th>Secondary Objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Exploration</td>
<td>- Economic and technological development</td>
</tr>
<tr>
<td>- International pride and prestige</td>
<td>- Science</td>
</tr>
<tr>
<td></td>
<td>- Education</td>
</tr>
<tr>
<td></td>
<td>- International collaboration</td>
</tr>
<tr>
<td></td>
<td>- Public-private partnerships</td>
</tr>
</tbody>
</table>

### 3 - The Future of the International Space Station

#### 3.1 - Current Status and questions

The question of the duration and nature of the United States’ future involvement in the ISS is of high importance to US spaceflight policy. The ISS has served as a model for international collaboration and provided insights that have helped advance human spaceflight and the sciences [41]. However, it has taken 25 years to assume full functionality and cost an estimated $100 billion to complete [17]. Currently, the ISS also costs $3-4 billion each year to maintain, half of NASA’s human spaceflight budget [42]. This high annual cost affects NASA’s ability to pursue other exploration plans beyond LEO. Despite these costs, the planned operation of the ISS has been extended multiple times, most recently by the Obama administration to its currently authorized deadline of 2024 [43]. The next administration should therefore weigh whether the continued use of the ISS past 2024 is the best way to accomplish the primary objectives of the human spaceflight program.

An additional component to the future of the ISS is commercialization. Significant commercial activity already exists on the ISS. These activities include the Bigelow Expandable Activity Module (BEAM), Cubesats, and 3D printing. Another significant example of commercial activity is the designation of a portion of the ISS as a national laboratory under the management of the Center for the Advancement of Science in Space (CASIS). However, CASIS has struggled to foster commercial interest in research on the ISS, due in part to the high costs of conducting research there [44]. Other examples of commercial activity on the ISS include the commercial resupply services and commercial crew program. While the cargo resupply services have proven to be a success in many regards, the commercial crew program has experienced delays that have forced the US to purchase more Soyuz seats to maintain access to the ISS [45]. As public-private partnerships are an explicit goal of current US civil space policy and a potential means of partially reducing program cost, it is also important to examine the question of ISS commercialization. The specific sub-questions examined in this work are:

**Q 1.1 – How long should the operation of the ISS be extended?**

**Q 1.2 – How can commercial activity on the ISS be expanded?**

#### 3.2 Existing Policy Options and Proposals

**Q 1.1** - The Trump administration originally proposed ending all direct federal funding to the ISS in 2025 [42]. While this would allow more funding for human exploration systems such as the Space Launch System, Orion, Lunar Gateway and lunar landers, it would also not allow for all the planned human research goals to be accomplished as can be seen in Figure 1. In 2019, the Trump administration released a revised plan that now supports continued federal funding of the station with incremental attempts to increase commercial activity [46]. Additionally, congress is currently considering bills which would extend the life of the ISS through 2030 [46].

**Q 1.2** - Commercial activity on the ISS already exists but has struggled to expand its scope (in the case of CASIS) and experienced delays (in the case of commercial crew). The Trump administration’s initial ISS transition report outlined many ambitious potential commercialization options including augmenting the ISS with private modules, forming a new platform out of portions of the ISS, and
investigating partnerships for private spaces stations in LEO [47]. While the Trump administration has pulled back from its initial plans to completely end federal funding for the ISS in 2025, the administration’s policy still seeks to expand commercial activity. This proposed policy includes: manufacturing commercial goods for sale on earth, allowing private astronauts to conduct commercial and marketing activities on ISS, and including US astronauts in commercial and marketing activities as well [48].

3.3 - Analysis and Recommendations

**Q 1.1** - The primary objectives of human spaceflight are best accomplished by ambitious exploration beyond LEO. The extension of the ISS is therefore best examined through the lens of how to use finite resources to accomplish these exploration goals quickly and successfully. The benefits and downsides of an extension are summarized in Table 2.

<table>
<thead>
<tr>
<th>ISS extension beyond 2024</th>
<th>Benefits</th>
<th>Downsides</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>- Accomplishment of human research goals</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Continued accomplishment of secondary objectives</td>
<td>- Continued diversion of NASA funds away from exploration beyond LEO</td>
</tr>
</tbody>
</table>

**Recommendation: The ISS should be extended through 2028.**

The extension of the ISS through 2028 would allow for NASA to complete its planned human research questions, for which extended access to microgravity is essential. This research is necessary to accomplish eventual deep space exploration safely and successfully. While this extension of the ISS will have the added benefit continued economic development, education, and science, it will also continue to cost NASA $3-4 billion per year, which led to our second recommendation:

**Recommendation: NASA should continue to examine paths for ending ISS involvement.**

A longer or indefinite extension of the ISS would be detrimental to exploration missions from a financial perspective. As the primary objectives of exploration and prestige are best accomplished through missions beyond LEO, the eventual allocation ISS funds to these missions is essential to their success. These missions will also continue to accomplish, technology development, education, and science and therefore are not to the detriment of the secondary objectives.

**Q 1.2** - Given that the ISS will operate through at least 2024, and likely be extended beyond that date, it is prudent to offset the cost of the station during this time through commercialization.

**Recommendation: All paths to increased ISS commercialization should be pursued.**

Commercial activity on the ISS accomplishes many of the secondary objectives, including the explicit objective of public-private partnership. These paths will include NASA’s on-going plans to bolster CASIS, continued use of commercial partners in cargo and crew transport, and the proposed use of the station for commercial goods and advertising. These activities have the added benefit of offsetting the cost of the ISS and will not adversely impact NASA’s microgravity and human research on the station.
4. Deep Space Exploration

4.1 - Past Plans

Human space exploration has not ventured beyond Low Earth Orbit (LEO) since the end of the Apollo program in 1972 [49]. During the George W. Bush administration, NASA attempted to develop new launch vehicles and spacecraft with the eventual goal of returning to the Moon under the Constellation program, however the program was plagued by scheduling and funding issues and cancelled by the Obama administration in 2010 [50, 11]. However, the Space Launch System and Orion were preserved from this program due to the support of key legislators. The Obama administration pivoted towards a new “Journey to Mars” plan for human exploration that entailed an earth reliant phase where relevant research on the ISS is continued, a “proving ground” phase that entailed a human mission to an asteroid and the development of an initial deep space habitat, and an earth independent phase with human missions to Mars.

4.2 - Current Plans and Questions

The Trump administration first issued Space Policy Directive 1 [13] to refocus on a return to the Moon. This return to the Moon originally entailed fully assembling the Lunar Gateway, a small orbital platform in the lunar vicinity for human operation, followed by a human lunar landing in 2028. However, this plan was criticized as lacking urgency by the National Space Council [51]. In 2019, the Trump administration proposed the Artemis program, which seeks to build a scaled down version of the Gateway, then land astronauts at the Lunar south pole by 2024 before establishing a sustained lunar presence by 2028 [52]. The Trump administration has maintained that one of the goals of lunar exploration is to prepare for a human mission to Mars. While NASA has begun awarding some contracts towards Artemis activities, the program has yet to receive full funding from congress [53]. In addition to the administration’s proposed lunar plans, there are also alternative proposals, such as Zubrin’s “Moon Direct” which criticizes the use of Gateway and calls for an alternative architecture for lunar exploration [54]. Given the various destinations and architectures that have been proposed by current and past administrations, this report examines two sub-questions:

Q 2.1 – What should be NASA’s ultimate deep space exploration goal?
Q 2.2 – Should NASA return humans to the Moon?

4.3 - Analysis and Recommendations

Q 2.1 - NASA’s ultimate exploration goal should be driven by what degree the destination accomplishes the primary objectives of exploration and cultivating international prestige. Mindell et al. examine the question of whether a lunar base as an ultimate goal might satisfy these objectives and conclude that the essential aspect of any exploration plans is that new policies be more ambitious than previous ones [17]. The 2014 National Academies report concludes that Mars should be the ultimate horizon goal as it best addresses the aspirational goals [6]. Despite other changes in policy, Mars has been the ultimate goal for the George W. Bush, Obama, and Trump administrations.

Recommendation: NASA should maintain Mars as its ultimate human exploration goal.

While exploration on the moon or to an asteroid would doubtlessly accomplish some of the objectives of human spaceflight to a degree, Mars is widely recognized as the most ambitious exploration goal accessible to humans in the foreseeable future. This ambitious goal would successfully accomplish the primary objectives of human exploration and international prestige. Additionally, as this goal will entail overcoming many technical challenges, it will lead to the accomplishment of secondary objectives such as technological and economic development and education. With Mars as the ultimate destination, the follow-up question is how do we plan intermediate exploration missions to best accomplish this goal?

Q 2.2 - Table 3 shows that a return to the moon would provide technical preparation for some aspects of a Mars mission such as experience with deep space habitats and in-situ resource utilization [38]. Additionally, any return to the moon, whether it be a singular mission or a sustained presence, would accomplish many of the secondary objectives of human spaceflight. However, there are some aspects of the Mars mission that are not addressed via a return to the moon such as the entry, descent and landing scenario as well as the distance and duration involved in a Mars mission [17]. Additionally, NASA’s current
estimates for the additional cost to accomplish the 2024 Artemis landing is between $20-30 billion on top of NASA’s existing budget, not all of which will go directly towards technologies that advance a Mars mission [55]. As the Artemis cost also calls for a sustained lunar presence, there will also be high annual costs associated with the current plans to return to the moon that could draw resources from a Mars mission.

**Recommendation:** A limited return to the lunar vicinity with an explicit plan to build capabilities towards a Mars mission should be pursued.

As mentioned above, a human mission to Mars is the horizon exploration goal that will most successfully accomplish the primary objectives of human spaceflight due to its ambitious nature as an exploration goal and the prestige that will accompany overcoming the considerable challenges such a mission presents. Therefore, the question of return to the Moon must be approached through the lens of how to most effectively accomplish this ultimate goal (see Table 3). Any mission to return to the Moon therefore should focus explicitly on developing technologies that directly work towards a human mission to Mars. The planetary society has echoed this sentiment in past reports, stating that future exploration plans should be developed such, “..that artificial schedule constraints do not drive programmatic decisions. In particular, human landings on the Moon should be deferred until after a new transportation and interplanetary flight capability is developed and validated. They should be conducted at the appropriate time if they are shown to be critical steps toward the development and validation of exploration capabilities, but they should not a priori be designated as the first step.” [56]. A return to the lunar vicinity with these guiding principles will work best to quickly and effectively accomplish the primary objectives of human spaceflight while still producing the benefits of the secondary objectives.

<table>
<thead>
<tr>
<th><strong>Table 3: Benefits and Downsides to Returning to the Moon</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Benefits</strong></td>
</tr>
<tr>
<td>Return to the moon</td>
</tr>
<tr>
<td>- Preparation for some Mars mission aspects (deep space habitat, ISRU)</td>
</tr>
<tr>
<td>- Benefits of secondary objectives</td>
</tr>
</tbody>
</table>

5. International and Public-Private Partnerships
5.1 - **Current Status and Questions**

In human spaceflight exploration today, there exists collaboration between the US and international partners, exemplified by the ISS. These international partners have provided physical modules and components for the station and aid in funding the station, helping to offset the impact on NASA’s human spaceflight budget. Of note is that international collaborations in human spaceflight have often occurred during times of international tension on earth, such as the Apollo-Soyuz docking between the US and USSR during the Cold War [57], and US-Russia collaboration on the ISS has survived more recent issues such as Russia’s invasion of the Ukraine [58]. These events point to human spaceflight as a means for bolstering international relations and diplomacy, another benefit of international partnerships in these endeavors.

The ISS currently serves as an opportunity for public-private partnerships as well. In addition to CASIS and commercial activity such as the Bigelow BEAM module, there are also the commercial cargo (Orbital ATK and SpaceX) and crew (Boeing and SpaceX) contracts that NASA has awarded. These contracts are NASA’s largest investment in public-private partnerships for human spaceflight, as transport of cargo and crew amounts to 50% of the ISS’s annual cost [42]. Additionally, the investment in these companies has allowed them to participate in deep space exploration, such as Orbital ATK’s plans to utilize the design of its Cygnus cargo capsule to produce the habitation module for the lunar Gateway [59].

However, while the ISS demonstrates many positive examples of these partnerships, one key player left out of these collaborations is China. Collaboration in human spaceflight between the US and China has been discouraged via American domestic policy including the Wolf Amendment. The Wolf Amendment
specified that no collaboration between the US and China can take place in the space sector without the approval of the FBI and congress [60]. The rationale for these policies include concerns about China’s human rights abuses and theft of American intellectual property [61, 62]. Despite these restrictions, China has had many successes in human spaceflight and has ambitious plans for the future. Three sub-questions with respect to these issues are examined in this report:

Q 3.1: What role should international and private partners play in the future of the ISS?
Q 3.2: What role should international and private partners play in deep space exploration?
Q 3.3: Should the US pursue opportunities for collaboration with China in civil space?

5.2 - Potential Policy Options

Q 3.1 – International partners have expressed interest in continuing collaboration on the ISS through any potential extension beyond 2024 [63]. However, this would require each of the partners to approve the extension through their own domestic processes. Also, the exemption to the Iran, North Korea, Syria Nonproliferation Act that currently allows the US to pay Roscosmos for services, expires at the end of 2020, so the US would also have to go through domestic processes to continue collaboration as it is currently structured [64]. Any extension beyond 2024 would also require extending existing contracts with private partners for cargo and crew transport, or potentially starting new partnerships for these services.

Q 3.2 – With respect to NASA’s current deep space exploration plan to return to the Moon, the exact nature of international collaboration is currently unclear. While the originally proposed Gateway plan called for the extensive international collaboration [65], with the revised Artemis plans for a scaled down Gateway international collaboration has been deferred [60]. The involvement of private partners in these future exploration plans is more certain however, with NASA already seeking commercial involvement in both the supply of cargo to the Gateway and the landing of payloads on the lunar surface [66, 35].

Q 3.3 – The question of whether to increase collaboration with China in civil space is subject to active debate within the US. While as recently as May 2019 language was introduced to a House appropriations bill that included similar restrictions to the Wolf amendment, experts from organizations such as Center for Strategic and International Studies as well as NASA leadership have expressed interest in expanding collaboration with China in space [60].

5.3 - Analysis and Recommendations

Q 3.1 – The downside of an ISS extension is its costs. Under current agreements, JAXA, ESA and CSA pay 12.8%, 8.3% and 2.3% of the cost of the US segment of the ISS respectively [42]. Additionally, in their transport of crew and cargo, provide important services for the ISS.

Recommendation: Continued international and private collaboration on the ISS beyond 2024 should be pursued

As these international and public-private partnerships offset the costs of operating the ISS, they allow its activities to continue to accomplish the secondary objectives of technological development, economic development and education, while mitigating the downsides of station operation. Additionally, international collaboration and public-private partnerships are secondary objectives of human spaceflight in themselves and therefore utilizing the ISS for this purpose accomplishes those objectives.

Q 3.2 – If international and commercial partners are involved in future deep space exploration efforts such as a return to the Moon, their involvement can help offset costs similarly to the ISS. Additionally, while previous deep space exploration plans have been subject to cancelation, agreements with international and commercial partners could help give these projects more momentum [67].

Recommendation: Extensive international and private collaboration on deep space exploration should be pursued

One of the primary objectives of human spaceflight is ambitious exploration that expands the human experience. Therefore, international and public-private collaborations that offset the cost of these efforts and build programmatic momentum serve to best accomplish this primary objective. Additionally, continuing and expanding these partnerships in future deep space exploration missions would accomplish the explicit secondary objectives of international collaboration and public-private partnerships.

Q 3.3: The motivations behind discouragement of cooperation with China in civil space are China’s theft of intellectual property and human right’s abuses, both of which are well documented concerns [68,
However, the fact that the US is alone in not collaborating with China, limits its ability to change Chinese policy with respect to human rights through restrictions in the space sector, and this policy has not slowed China’s rise as a space power [62, 60]. Additionally, the US is at risk of being left of our future human spaceflight collaborations as evidenced by current ESA-China collaboration on astronaut training [70]. Lastly, despite the strong restrictions in place, limited but successful examples of US-China collaboration in space already exist, such as the recent collaboration between NASA’s Lunar Reconnaissance Orbiter on China’s robotic lunar landing of Chang’e – 4 [60]. The benefits and downsides of this lack of cooperation are summarized in Table 4.

**Recommendation: Pursue opportunities for collaboration with China in civil space**

Increasing collaboration with China in civil space would advance the primary exploration objectives of human spaceflight. As the world’s second largest economy and a nation that has already accomplished successful independent human spaceflight milestones, the financial and intellectual resources in this collaboration would advance ambitious exploration goals. Additionally, the history of US-Russian collaboration in human spaceflight shows that successful partnerships in space can be achieved despite strong geopolitical differences on Earth. Opportunities to collaborate with China therefore also have the potential to accomplish the secondary objective of international collaboration.

**Table 4: Benefits and Downsides to Discouragement of US-China Collaboration in Space**

<table>
<thead>
<tr>
<th>Discouraged Cooperation with China in Civil Space</th>
<th>Benefits</th>
<th>Downsides</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Potential to prevent loss of IP</td>
<td>- Has not slowed China’s rise in space</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Potential to be left out of future collaborations (ESA and China)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Limited examples of successful collaboration (Chang’e 4)</td>
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</tr>
</tbody>
</table>

**6. Outreach**

Outreach was conducted at Jackson Mann K-8, a public school in Allston, MA. A presentation on human spaceflight was given to a 6th grade math class. The content of the presentation included the history of NASA’s human spaceflight efforts, current activity in human space exploration, and future plans for deep space exploration (see appendix). The students were very interested in the subject matter and after the presentation concluded, asked a wide variety of questions until the class period concluded. As this outreach effort was a success, future presentations at Jackson Mann may occur in the future.

**7. Conclusion**

The primary objectives of the U.S. human spaceflight program are the cultivation of international prestige and the expansion of the human experience through ambitious exploration missions. Additionally, secondary objectives of economic and technological development, science, education international collaboration, public-private partnerships are important benefits that can be derived from human spaceflight. In order to best utilize the large investments the US makes in the human spaceflight program, it is essential to analyze future policies through the lens of these objectives. With respect to the ISS, extending the operation of the station to fulfill human research goals will aid in future exploration efforts while increased commercialization will help offset the annual costs. Looking beyond LEO, NASA should keep Mars, the most ambitious exploration destination currently within humanity’s reach, as its ultimate exploration goal and utilize a limited return to the lunar vicinity to explicitly prepare for this mission. Both current efforts on the ISS and future deep space exploration efforts will benefit from continued collaboration with international and private partners, and expanding opportunities for collaboration with China will also aid in achieving ambitious human space exploration goals as a global community.
References


U.S. Policies on International Cooperation for Human Spaceflight

Cody Paige and Jessica Todd

May 2020

1 Overview

1.1 Historical Context

International cooperation has underpinned NASA policy since the agency’s inception. The National Aeronautics and Space Act of 1958, which led to the establishment of NASA, incorporated international cooperation directly into its policies, with the direction that NASA could “engage in a program of international cooperation in work done pursuant to this Act, and in the peaceful applications of the results thereof” and within 6 months NASA had begun to develop a program of international cooperation in space, primarily focused on early scientific endeavours. Indeed international collaboration has been a critical component of NASA’s success in human spaceflight since the first Mercury missions. Due to the need for effective ground control during full orbital missions, a worldwide tracking and telemetry network was developed involving system development, installation, site locations, testing, and training in Australia, the United Kingdom, Nigeria and Spain. These facilities were critical for monitoring capabilities in the highest probable abort phase of launch through insertion and for the critical reentry phase after orbital flight. International involvement remained a key aspect of human spaceflight through the Gemini and Apollo missions, with the Moon landing audio and pictures being carried to American televisions from stations in Australia and Spain. This global network created a sense of camaraderie in the accomplishment of the lunar landing. This is exemplified by astronaut Michael Collins recalling the world’s reaction after the Apollo moon landing, international viewers exclaiming ‘We did it!’ [JFK Library Apollo 50th anniversary]. The early human spaceflight program also set the stage for NASA’s influence in soft diplomacy.

While the Apollo era was typified by competition with the Soviet Union, a chance for the US to demonstrate technological and political superiority, the concept of expanded international space cooperation began at senior levels within the US government in the mid-1960s. After the success of Apollo 11, NASA and President Nixon made a conscious decision to expand international partnerships in post-Apollo space efforts, focusing on two aspects: (1) inviting U.S. allies to participate in technology development and human spaceflight, and (2) engaging the Soviet Union in substantial cooperation. Early engagement with Canada and Europe led to collaborations on the Space Shuttle program, including the Remote Manipulator System (Canada) and Spacelab (Europe), and the beginning of what would become the International Space Station.

After the moon landing, it was work in Human Spaceflight that formed the basis of Soviet-US cooperation moving forward. In 1970, NASA Administrator Thomas O’Paine proposed collaboration focused in the area of astronaut safety, and in developing a compatible rendezvous and docking system between the US and Soviet Spacecraft. This joint work laid the foundation for all future Russian-American cooperation in Human Spaceflight, the centrepiece of which was the Apollo-Soyuz Test Project throughout the 1970s. US-Russian cooperation went on to become the cornerstone of the International Space Station and of NASA’s international human spaceflight activities. The original partnership agreements for the ISS were signed in 1988 between the U.S., Europe, Japan and Canada. In 1998, 15 countries gathered in Washington to sign an updated framework for the cooperation on the design, development, operation and utilization of the International Space Station. These new agreements were signed as a result of significant Russian involvement in the program. NASA’s international partners were able to actively contribute to a highly visible multinational scientific effort, with
well-defined contributions and ownership, while NASA benefited from its foreign partners expanding on the capabilities of the space station, and sharing in the costs and development.\textsuperscript{5}

The value of international cooperation in human spaceflight cannot be overstated. The ISS is, to date, the longest and most expensive international scientific and technological collaboration ever undertaken. The multilateral agreements put in place for the ISS have withstood global tensions and have paved the way for future international deep space missions.

Since its inception in 1958, NASA has made international space policy one of its primary activities. There have been over 4,000 agreements with over 120 nations and international organizations.\textsuperscript{6} Currently there are 700 active international agreements with over 50% of those accounted for by France, Germany, ESA, Japan, Italy, Canada and Russia. Fig. 1 shows the breakdown of agreements by region and their type. It is clear that Science is the primary area for international cooperation at 71% of the agreements, with Human Exploration and Operations consisting of only 16% of the agreements.

![Figure 1: Left: International agreements with NASA broken down by region, and Right: International agreements by Mission Directorate](image)

1.2 Administration And Policy Overview 2010-2020

Various senate and congressional bills and NASA authorization acts have subsequently addressed International cooperation with regards to Human Spaceflight. As each new administration re-scopes NASA priorities and overall goals, motivations and commitments to international cooperation shifts. Below are highlighted several of the proposed and enacted NASA Authorization Acts over the past decade.

1.2.1 NASA Authorization Act of 2010 (S.3729)

The NASA Authorization Act of 2010, sponsored by Senator John D. Rockefeller IV (D-WV),\textsuperscript{7} authorized NASA appropriations for the fiscal years 2011, 2012 and 2013, and was enacted into law by the 111\textsuperscript{th} Congress, during the Obama administration.\textsuperscript{8} With regards to the Human Spaceflight Program, the core of the Act is the refocusing of the Constellation program, including renewed funding for the Orion crew capsule and Ares I rocket, as well as provisions for the retirement of the Space Shuttle, and extension of ISS operations to at least 2020. The 2010 Act proposes that expansion beyond low-Earth orbit will enable missions to the surface of the Moon, near-Earth asteroids, and Mars.

Maintenance of current international partnerships, and an integrated international approach to deep-space exploration appear to be at the core of the vision outlined by the 2010 Authorization Act. The Act outlines NASA’s long-term goal to “expand permanent human presence beyond low-Earth orbit, and to do so, where practical, in a manner involving international partners”\textsuperscript{9} [202.a]. International cooperation in human spaceflight that builds on the experience and framework of the ISS agreements is highlighted as one of four key objectives of US human expansion into space, with international partner discussions input requested for an independent review of a Human Exploration of Space study [204.b]. The ISS is highlighted as a key component of international efforts to build missions
and capabilities for deep space [502.b]. The Authorization Act frequently makes reference to the international exploration of deep space, opening up the possibility of investing in space-transfer vehicle technologies to facilitate international efforts to expand human presence into deep space [308.b.2.C], and directing the establishment of in-space capabilities and resource utilization that contribute to the extending of human presence in space in an international manner [502.b.2].

1.2.2 NASA Authorization Acts of 2014 (H.R.4412) and 2015 (H.R.810)

The NASA Authorization Acts of 2014\(^9\) and 2015\(^10\) (sponsored by Rep. Steven M. Palazza (R-MS-4)) were not enacted into law by Congress, however an examination of the language of these bills sheds light on the changing approach to international cooperation throughout the past decade.\(^{11,12}\) These Authorization Acts focus largely on the Space Launch System and Orion vehicle, amending the Vision for Space Exploration put forward by President Bush. The 2014 Act outlines that “Human exploration deeper into the solar system shall be a core mission of the administration” [201.a] however much less emphasis is placed on the role of international partners. Both Acts emphasize a need for the US to pursue international and intergovernmental means of logistics supply, maintenance, and operation capabilities for the ISS, particularly as a way to reduce costs to NASA, and the Acts highlight the need to plan for intermediate human exploration destinations with international collaboration, along the path to Mars. A key difference between the 2014 and 2015 Acts, as compared to the 2010 Authorization Act, is that the goal of reaching Mars is re-framed from a joint international endeavour, instead directing that the “President should invite US partners in the ISS and other nations as appropriate in an international initiative under the leadership of the US to achieve the goal of successfully landing a crewed mission on the surface of Mars” [202.b]

1.2.3 NASA Transition Authorization Act of 2017 (S.442)

The NASA Transition Authorization Act of 2017 was the first comprehensive NASA authorization passed by Congress since 2010.\(^13\) The bill appropriates $4.33 billion for exploration for the fiscal year 2017, and a further $5 billion for space operations, including the International Space Station. The language of the 2017 Act shows a clear shift in international space policy from the NASA Authorization Act of 2010. The bill reiterates the goal of the 2010 Authorization act that one of NASA’s goals shall be “to expand permanent human presence beyond low-Earth orbit and to do so, where practical, in a manner involving international, academic, and industry partners” [411.a.1], however the bill makes it clear that international deep space missions will take place under US leadership. Under the Stepping Stone approach to human exploration laid out in the Act, international cooperation is highlighted as a priority to maximize cost-effectiveness of long-term space exploration [414.b] and using the same language as the 2014/2015 Acts, that the President may invite other nations to participate in an international crewed mission under US leadership [414.d]. Throughout the 2017 Authorization Act it is made clear that maintenance of US leadership in space is an imperative, though this can be conducted with our international partners. The Bill directs the Administrator to put together a new Human Exploration Roadmap with clear mission steps towards Mars, highlighting that to achieve sustained US leadership in space, exploration objectives need to be addressed in collaboration with international, industry and academic partners [432.a.2], and that opportunities for international partnerships should be included in the roadmap if those opportunities provide ‘cost-savings’ or ‘accelerate program schedules’ [432.b].

With regards to the ISS, pursuing international collaborations are discussed as a means to reduce risk to the sustainability of ISS operations and to offset and minimize US ISS costs [201]. The 2017 Act does place an emphasis on continuity of purpose in US Space Policy, ensuring that current commitments are honours are built upon [201].

1.2.4 NASA Authorization Act of 2019 (S.2800)

This authorization act was put forward by Senator Cruz, with a focus on meeting the goals laid out in the 2010 Authorization Act established by President Obama.\(^14\) The Authorization Act appropriates $6.2 billion for Exploration under the Human Spaceflight and Exploration program. With regards to international collaboration, the act specifically directs the Administrator to “collaborate with commercial and international partners to establish sustainable lunar exploration by 2028” [201.b]. It instructs
NASA to develop no more than two lunar landers and continue SLS development to meet the goals of the 2010 Authorization Act, in pursuit of this sustained lunar presence. The Authorization Act outlines a stepping stone approach to human exploration of the Solar System, highlighting the need for sustainable intermediary steps leading to a Mars landing [216].

The language of the 2019 Authorization Act highlights a key US international space policy. The Rule of Construction states that nothing in the act should prohibit the Administrator entering into no-exchange-of-funds collaborative agreements with international partners in support of NASA deep space exploration.

1.2.5 NASA Bill H.R.5666

The H.R. 5666 bill, introduced by Representative Kendra Horn, in a very broad sense aims to reorient the NASA human space exploration goals towards Mars by limiting the resources to be allocated towards lunar exploration to activities that will enable first footprints on Mars. Many aspects of this bill will help to keep NASA from falling into a pattern like that of the ISS in which lunar endeavors take over primary spending, essentially restricting us from reaching Mars. However, the bill is too rigid in its explicit direction of how the goals for deep space exploration will be reached, using verbiage which may hinder international involvement. Some examples of this verbiage as pertaining to international development include:

- Limiting technological development providers (Moon) - international collaborators will not want to relinquish all intellectual design to NASA [203.f.4][205.c]
- Prevention of commercial firms from participation in lunar lander bids [205.b][205.g]
- Limiting conduct of Mars-relevant research on the lunar service [205.c]
- Separation of Gateway from lunar landings [205.a]
- Non-critical path activities will not be part of the Moon to Mars budget: Continuously crewed lunar outpost or research station, Non-Mars related crewed activities on or near the moon and Lunar in-situ resource utilization (ISRU) [206]

Some of the main concerns I highlighted here demonstrate the restrictiveness of the bill. For instance, ISRU may prove to be a critical activity for achieving a human Mars mission given the mass reduction possibilities if water and fuel could be produced on the Mars surface instead of transported to Mars. This is an arena where international cooperation is of major value. The CSA is awarding seven contracts worth a total of $4.36 million to advance concepts for miniaturized rovers and autonomous science instruments for lunar exploration. They have also contributed significantly to past Mars rover missions, including Curiosity and the Mars Science Laboratory.

Many of the international collaborators are interested in human spaceflight as an incentive to contribute technology to NASA missions. Limiting or excluding Mars-relevant research, lunar landings, and continuously crewed lunar outpost research will limit the number of international astronauts permitted to participate in lunar missions which may cause a reduction in international partners.

1.3 Historical Partnership Goals: the International Space Station

The International Space Station is a key milestone in international partnership. It is a co-operative program between the United States, Canada, Russia, Europe and Japan for the ‘joint development, operation and utilisation of a permanently inhabited Space Station in low Earth orbit.’ Such a unique shared platform required a unique legal framework to define the rights and obligations of each country, their jurisdiction and control. The agreement has been signed by fourteen governments. There are three levels of international co-operation agreements that form the legal framework: The ISS Intergovernmental Agreement (IGA), the four Memoranda of Understandings (MoU), and the bilateral Implementing Arrangements. The IGA is a treaty which establishes the long term design, development, operation and utilisation of the station, detailing how to peacefully and permanently inhabit the station. Because the US and Russia had extensive experience in human spaceflight, the IGA specifies that this experience will allow these countries to produce the foundational elements of the ISS, ESA and Japan would contribute ‘elements that will significantly enhance the Space Station’s
capabilities\textsuperscript{17} and Canada’s contribution, the Canadarm, would be an essential part of the station. The IAG encompasses 28 Articles defining every aspect from international rights and obligations to transportation to criminal jurisdiction. The MoUs are space-agency level agreements which more specifically address the roles of each agency and provides a management structure and interfaces. Many of the topics addressed in the MoUs are direct reflections of the IAG, providing more concrete assignments of the agreed upon roles and responsibilities. The ISS is described in detail with each element outlined\textsuperscript{18} with each MoU addressing the relationship between NASA and one of the other founding members. Finally, the bilateral Implementing Arrangements are used to implement the MoUs, distributing concrete guidelines and tasks among the agencies.\textsuperscript{16}

Ownership of the ISS is defined as allowing the partners to extend their national jurisdiction in outer space, meaning the elements they provide to the station become territories of their respective states. This means they are also legally responsible for these elements, extending their laws and regulations to not only the specific module, but the equipment and personnel as well. For use of the ISS and its elements, the partners have the right to use any of the elements they provide and when they provide resources and infrastructure needed to operate the ISS, they receive a fixed share of the use of certain other elements. This works on a barter system allowing partners to exchange unused elements among themselves as well as with non-participant countries, this is a no-exchange-of-funds policy enabling a reduction of technical and financial risk in operation of the station. Liability is based on the Liability Convention (1972) and establishes a ‘cross-waiver of liability’ which prohibits the partners to claim against one another for damages sustained as a result of ISS activities, with some exceptions, such as willful misconduct. Intellectual property is also addressed to mitigate the risk of potential infringement. They created specific marking procedures to protect proprietary and confidential data and goods while ensuring that when necessary to operate the ISS, specific data and goods must be shared.

The legalise set forth at the onset of the ISS established a long-term working relationship for a truly multi-national community in space. The ISS is a shining example of the political power that human spaceflight has in forming lasting global relationships.

## 2 Case Studies

We now review a cross-section of Case Studies which reflect the varied international participation in human spaceflight throughout history as well as what this will look like going forward. These Case Studies will be used to assess the implications of changing policy on international relationships and the benefits to both NASA and their partners in maintaining them.

### 2.1 Historical Monetary Commitments

As international partnerships are established for the Artemis program and the Lunar Gateway, questions arise as to the efficacy of enlisting non-domestic industries for critical deliverables. While it can be argued that the soft diplomacy gained from these international partnerships are well-worth the extra developmental costs, it is important to assess if this is the only benefit.

#### 2.1.1 Case Study: the Canadarm as a long-term investment

The Canadarm3 is one such investment with a history that dates to the Shuttle era. Investigating the technology used in the original Shuttle Canadarm and the associated costs and timelines of development we make the case that the same robotic technology from a domestic company would have had a considerably longer development timeline and hence higher implementation cost than the Canadarm. Following this, the cost of the Canadarm2 for the ISS was kept to a minimum by building on proven technology. Now, as we approach the Canadarm3 development for the Lunar Gateway, we should be confident that there are significant cost savings in employing an international developer.

Below is a historical timeline of significant developments in robotic arm technology. Because of the development of the CANDU nuclear reactor arm in 1968, which required a functional, industry tested robotic arm with an end effector to operate in a hazardous environment, Canada had the most relevant candidate for the Shuttle robotic arm. While the U.S. was a leader in robotics at the time, the developments were still primarily in the academic sphere and focused on the automotive industry, thus missing the key environmental operations requirement. Key highlights include:
• 1968: Second CANDU nuclear reactor is operational in Canada with hazardous environment manipulator arm. Continuous operation until 1975 (Contract awarded for Shuttle Manipulator Arm in 1975)
• 1969: Stanford Arm development – academic manipulator arm
• 1975: Industrial robotic arm PUMA is developed for automotive manufacturing
• 1975 – 1981: Shuttle Manipulator Arm development
• 1977: JPL parallel study of robotic manipulator arms
• 1986 – 2001: Canadarm2 development

Canada’s 7-year experience with the CANDU arm provided the foundation for the 6-year development and launch of the Canadarm and subsequent 7 year development of the Canadarm2 – similar development timelines reflect the advanced state of technology in place prior to the development of Canadarm.

Table 1 shows a summary of Canada’s development costs for the Canadarm through the Canadarm3 with contract costs from NASA. The costs are reported in current US dollars. It is of note that the development for the Canadarm2 is roughly equivalent in cost to the original Canadarm. This highlights the reuse of technology used for the Canadarm. If the technology had been in an earlier phase of development the Canadarm costs would have been much higher than the Canadarm2, since it was building on technology. This would also have been reflected in the NASA contract costs.

### Table 1: Canadarm Cost Breakdowns

<table>
<thead>
<tr>
<th></th>
<th>Development Cost (USD Millions)</th>
<th>NASA Contract (USD Millions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canadarm</td>
<td>220**</td>
<td>108**</td>
</tr>
<tr>
<td>Canadarm2</td>
<td>200**</td>
<td>150**</td>
</tr>
<tr>
<td>Canadarm3</td>
<td>7.8 (robotics interface only)</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Between the minimized timeline and cost, it is clear there was more than just a political advantage in awarding Canada with the robotic arm development contract. This should be used as an example for justification of future international agreements.

### 2.1.2 Case Study: Australia as a new and old partner in space

While larger monetary agreements with agencies like ESA, JAXA and CSA will likely form the backbone of the Artemis International Partnerships, NASA is forming smaller agreements with emerging space countries like the UAE and Australia. Australia has been a long-term partner of the United States in human space exploration, with a historic collaboration dating back to the very advent of the Mercury program. NASA built tracking stations across Australia, used for Projects Mercury and Gemini, the Application Technology Satellite Program, the Apollo and Apollo-Soyuz programs, and which played an integral role in the Apollo 11 mission, returning mission voice and telemetry, and the television broadcast for the historic Moonwalk. The Canberra Deep Space Communications Complex is still operational today as part of NASA’s Deep Space Network, supporting NASA’s interplanetary missions including the Voyager missions and Mars Science Laboratory. It is operated by the Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia’s national science agency. Australia’s remote outback has historically been a proving ground for NASA, with analogue human and robotic missions being simulated there such as the Mars 2020 rover launching later this year. Historically NASA and CSIRO have collaborated on remote sensing and tracking research, with additional tracking stations in Alice Springs and Dongara in Western Australia used to support communications with the International Space Station.

On July 1st, 2018 Australia officially launched its own National Space Agency with the primary goal of coordinating Australian domestic commercial activities and supporting the growth of the Australian space industry. In September 2019, the Australian government signed a letter of intent between NASA and the newly formed Australian Space Agency, outlining a significant commitment by Australia towards NASA’s goal of returning astronauts to the Moon. This commitment included an investment of $150 million over five years for Australian business and researchers to deliver key capabilities towards
the Artemis mission. Funding will commence in 2020-2021 (likely 2021 given the current COVID-19 pandemic) with the next step involving a confirmation of interests between NASA and the Australian Space Agency that align with the Australian Civil Space Strategy 2019-2028 and the US interests in the Artemis program. This memorandum serves to summarise the history of US-Australian collaboration in space and highlight areas of potential interest within the Australian Space Sector to the current Artemis Plan.

With the formation of the Australian Space Agency, this $150 million represents a significant commitment on the part of the Australian government to investing in US-Australian cooperation, and to expanding cooperation beyond the historic tracking program. The Australian investment will focus on three key areas:

1. Demonstrator and pilot projects which showcase investment-ready Australian capabilities to NASA and the U.S.’s international space supply chains (e.g. in the areas of robotics, automation, Artificial Intelligence, and earth observation)

2. Working with NASA to identify how Australia can support a significant part of NASA’s ‘return to the Moon and on to Mars’ program, leveraging Australia’s key strengths (e.g. drawing on the demonstrator and pilot projects)

3. Supporting access to international space supply chains that support NASA, including capability building to help the Australian space sector meet the stringent requirements of supplying products and services in the global space industry

Most significantly, Australia is demonstrating significant investment in the fields of automation, robotics, and remote asset management. A $4.5 million Robotics, Automation and AI control centre will be established in West Australia with the purpose of researching autonomous on-orbit systems. The Australian mining industry has been investing heavily in these technologies over the past decade with great success, and with the NASA plans for a Lunar Gateway and remote lunar and Mars operations, Australia could be a highly beneficial partner in offsetting the costs of research and development, and supporting NASA’s Artemis timeline.

Collaborating with emerging space countries could be highly beneficial, allowing NASA to leverage technological expertise from other industry sectors within these countries, without having to significantly invest monetary funds into these sectors themselves or significant investment into technology development. Reciprocally, these countries can be aided in growing their local space industry by drawing on the wealth of experience NASA can offer in an advisory capacity.

2.1.3 Case Study: ESA - the option of human spaceflight

ESA has 22 member countries, each of which must subscribe to, or fund, projects which ESA classifies as mandatory, and may choose to fund the optional programs. Human spaceflight is categorized as optional. These optional program budgets are reviewed once every three years by the ESA Ministerial Council, requiring a 3-year budget proposal. The mandatory programs are required to have a 5-year budget proposal so that programs may continue uninterrupted in the event that a council meeting is disrupted or delayed. The largest contributors to ESA’s budget are Germany, France, and the UK. Fig.2 below shows the breakdown of the 2020 ESA Budget by country and the budget breakdown by domain.

Figure 2: Left: 2020 ESA budget broken down by country, and Right: 2020 ESA budget broken down by domain, both from.
Here we examine the breakdown of contributions by program for these countries. The most prominently funded programs are shown in Table 2

<table>
<thead>
<tr>
<th>Program</th>
<th>Country</th>
<th>Budget</th>
<th>% of Budget</th>
</tr>
</thead>
<tbody>
<tr>
<td>Science</td>
<td>Germany</td>
<td>112</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>France</td>
<td>90</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Italy</td>
<td>56</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>UK (Mandatory)</td>
<td>88</td>
<td>35</td>
</tr>
<tr>
<td>Earth Observation</td>
<td>Germany</td>
<td>155</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>France</td>
<td>182</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>Italy</td>
<td>37</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>UK</td>
<td>55</td>
<td>22</td>
</tr>
<tr>
<td>Telecommunications</td>
<td>Germany</td>
<td>52</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>France</td>
<td>44</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Italy</td>
<td>26</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>UK</td>
<td>58</td>
<td>23</td>
</tr>
<tr>
<td>Human Spaceflight</td>
<td>Germany</td>
<td>310</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>France</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Italy</td>
<td>32</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>UK</td>
<td>35</td>
<td>14</td>
</tr>
<tr>
<td>Launch Capabilities</td>
<td>Germany</td>
<td>223</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>France</td>
<td>403</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>Italy</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>UK</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Technology</td>
<td>Germany</td>
<td>24</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>France (Defense)</td>
<td>280</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>Italy</td>
<td>93</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>UK</td>
<td>8</td>
<td>3</td>
</tr>
</tbody>
</table>

Clearly, human spaceflight is not the top priority of most of these countries, in fact, France reported no budget specifically for human spaceflight at all. However, given that human spaceflight is deemed an optional program by ESA, those countries that do select to fund these programs provide a significant contribution to human spaceflight programs in general, as described below.

Of ESA’s €6.68 billion budget, 9.7% is for human and robotic exploration. The equivalent USD ESA budget would be $700.5 million. We compare this to NASA’s human spaceflight operations budget, including Orion, Gateway, ISS, Space Launch System and crew and cargo programs, of $9,539.2 million. However, if we exclude the SLS, space transportation and flight support budgets, this becomes $3,738 million. We remove the aforementioned budgets as the ESA budget does not include their launch system developments and systems support and so this is a more apt comparison. Using these reduced budgets then, ESA’s support is approximately 16% of the combined budgets. For an expensive endeavour, such as human spaceflight, this is a significant contribution to the efforts.

### 2.1.4 Case Study: United Arab Emirates - a small space program with big plans

The United Arab Emirates (UAE) is a fairly recent player on the international space stage, however since creating United Arab Emirates Space Agency (UAESA) in 2014 the country has made big strides in research and development, human spaceflight, and in fostering international partnerships in space. In June 2016, UAESA signed an agreement with NASA to cooperate on ground-based and sub-orbital research, research and flight activities in low-Earth orbit, and human and robotic exploration in lunar and cis-lunar space. Following this, UAESA established an astronaut corp and human spaceflight program with the goal to put an Emirati astronaut in space by 2021. This program within the new agency is seeking to create a sustainable human spaceflight program heavily grounded in science, to align with the UAE’s Mars 2117 program, a concept to establish a human settlement on Mars. In 2018, the UAESA signed a historic cooperative agreement with NASA, building on the initial framework of the 2016 agreement, to cooperate in Human Spaceflight. While the UAE is not a member of the consortium of countries that participate in the ISS, the international agreement enables training for UAE astronauts, as well as the opportunity for the UAE to utilize the ISS and contribute to lunar exploration. This signing of this agreement, and the establishment of an astronaut corp, appears to have propelled the UAE human spaceflight forward, with the first UAE astronaut, Hazza Al Mansoori, flying an 8-day mission to the International Space Station in 2019 alongside NASA Astronaut Jessica.
Meir and Russian Cosmonaut Oleg Skripochka. Mr. al-Mansoori was trained by ESA, JAXA, NASA, and Roscosmos, and purchased a seat to the ISS in the same manner that space tourists to the ISS do. Consequently NASA has referred to Mr. al-Mansoori as a spaceflight participant rather than a professional astronaut, however the international agreement signed by both NASA and the UAESA paves the way for future Emirati astronauts to fly to the ISS and beyond in a more official capacity.

2.2 Commitments to deep-space exploration

Moving forward from these present day and historical contributions, we now look forward to the Lunar Gateway, which represents a decades long commitment of collaboration between many space agencies, with formal commitments from Canada (CSA), the EU (ESA), Russia (Roscosmos), Japan (JAXA), and Australia (ASA). As the leading nation in this endeavour, the United States holds a responsibility to its foreign stakeholders to ensure the continuation of the project despite policy change. We continue with our case studies, doing a preliminary analysis of the ESA, Australian and Canadian investment strategies as indicators of the risks associated with committing to the Lunar Gateway for international agencies.

Despite the words of Dr. Greg Austry (Trump transition White House Liaison at NASA) that “Calling [the existing station the] ‘International’ [Space Station] is almost a farce. . . . There’s no doubt we could do it by ourselves”, space exploration is an international collaboration not just for the technological know-how of multiple nations and budgetary influx, but for its critical role in soft diplomacy as well. Recognizing the risks that the U.S.’s international partners take in committing to decadel long projects is key in ensuring these projects do not get cancelled with change in government leadership.

2.2.1 International Monetary Investments

Australia (ASA):

- Will invest $150 million over 5 years, intended to drastically increase Australia’s investment in space technologies and foster technology developments within academia and industry.
- **Key Focus:** Support of space start-up companies, environmental monitoring and international relationships

Canada (CSA):

- Will invest $2.05 billion over 24 years, this is intended to create hundreds of jobs and contribute $100 million annually to Canada’s GDP.
- The investment includes $150 million over 5 years in support of LEAP – intended to develop new technologies to be used and tested in lunar orbit on the Moon’s surface with small and medium-sized businesses.
- By 2021 Canada will have spent $556 million in financial resources towards the new space program directed towards the Lunar Gateway.
- **Rate of return on investment:** based on a five-year rolling average to set targets as missions proceed through their life-cycles. The investment-return lifecycle exceeds the 4-year presidential term associated with potential program cancellations.
- MDA Robotics, the company who built the Canadarm, was purchased by Canadian investors for ~ $765 million to keep the Canadarm 3 proposal to maintain Canadian propriety over the Canadian contribution to the Lunar Gateway.
- The CSA has awarded MDA 2 contracts for a total of $7.89 million CAD for the development of the robotic interfaces for the “exploration large arm” (Canadarm) and the “exploration dexterous arm” (DEXTER) – Phase A of the development.
- **Key Focus:** Canadarm3 operation and maintenance on Gateway and a sustained human presence at the moon (increased research in robotics and deep-space human health implications).
European Countries (ESA)

- Has committed $330 million (USD) for Gateway over the next 3 years\textsuperscript{31}
- $165 million for robotic lunar missions over the next 3 years\textsuperscript{31}
- ESA will provide the Orion service module

- **Key Focus:** For human exploration, ESA’s main commitments are to the continued operation of the **ISS** (committed to 2024), **Gateway and Orion**, with 25\% of their $2.4 billion (USD) human exploration budget for **lunar activities**\textsuperscript{31}

2.2.2 International Astronaut Involvement

The selection of international astronauts is part of the partnership agreements made between NASA and the international partner and works fundamentally like a barter system. The agreements are made on a program by program basis, evaluating the country’s monetary equivalent contribution, their interest in human spaceflight, and the longevity of their relationship with NASA. During the shuttle program, international astronaut participation was much higher as the number of American seats available for negotiation were higher. With the transition to the Soyuz, NASA and Russia share the 6 annual seats 50/50. This means that NASA only has 3 seats to not only fly US astronauts, but to negotiate with all of its international partners as well. Although the SpaceX Crew Dragon has capacity for 7 astronauts, NASA currently only has commitments for 4 astronauts on the first 6 missions, however, they have also contracted 4 seats on the Boeing Starliner’s first 6 missions to the ISS.\textsuperscript{51} This will be a marked increase in available seats with which NASA can barter with its international partners.

Currently, astronaut time and research is allocated to space agencies based on the money or the amount of resources they have contributed to the ISS. To date, 240 astronauts have visited the ISS from 19 different countries.\textsuperscript{52} Fig. 3 shows the breakdown by country of participating astronauts. Included in Table 3 are some of the major modules and components on the ISS.

<table>
<thead>
<tr>
<th>Contributing Agency</th>
<th>Astronauts Flown</th>
<th>Component</th>
<th>Launch Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roscosmos</td>
<td>48</td>
<td>Zvezda</td>
<td>2000</td>
</tr>
<tr>
<td>CSA</td>
<td>8</td>
<td>Canadarm2</td>
<td>2001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dextre robotic hand</td>
<td>2008</td>
</tr>
<tr>
<td>ESA</td>
<td>18</td>
<td>Columbus Orbital Facility</td>
<td>2008</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Leonardo Permanent Multipurpose Module</td>
<td>2011</td>
</tr>
<tr>
<td>JAXA</td>
<td>9</td>
<td>Japanese Experiment Module (Kibo)</td>
<td>2008</td>
</tr>
<tr>
<td>NASA</td>
<td>151</td>
<td>Truss System</td>
<td>Lifetime</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Destiny Laboratory Module</td>
<td>2001</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Harmony/Node 2</td>
<td>2007</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cupola and Tranquility/Node 3</td>
<td>2010</td>
</tr>
</tbody>
</table>
As defined by the IAG, each ISS partner has ‘the right to qualified personnel to serve on an equitable basis as space Station crew members.’ Selection of the flight assignments of crew members is made based on the MoU agreement in place with that member. For example, in 1998 when the NASA-RSA MoU was signed, because only NASA and Russian were sharing common system operations responsibilities (the other members had not yet contributed), NASA and Russia were each allocated 50% of the three-crew flight opportunities. It was also agreed that as other members began to contribute the allocations would be adjusted to allocate flight crew time to these members but would maintain the equal share of the remaining time for Russia and the US. It was established that after the ISS could maintain a crew of seven, Russia would be allocated three crew flight opportunities with the remaining four allocated to NASA (76.6%), GOJ (JAXA) (12.8%), ESA (8.3%) and CSA (2.3%).

A Multilateral Coordination Board (MCB), formed by the ISS partners, established a Multilateral Crew Operations Panel (MCOP) which is responsible for criteria for selection, certification, assignment and training of Space Station crew. A partner must propose their candidates for ISS crew based on mission requirements and allocated flight opportunities (defined in their MoU) and the MCOP determines if the candidate meets all of the criteria, and if they do, they assign them to specific crew complements which must be approved by the partners’ internal agency procedures.

For our case studies we explore the different levels of involvement of each and assess the contributions which were required to allow participation.

**Australian:**
To date, no Australian citizen has been invited to fly on a NASA human spaceflight mission. Australia does not currently have an astronaut program. Because involvement is awarded by program and Australia has only just formed a Space Agency, their contributions directly to the ISS have been minimal. Australia’s space exports have been from space start-ups and the Canberra Deep Space Communications Complex supporting NASA’s Science Directorate.

**Canadian:**
NASA first invited a Canadian astronaut to participate in a space mission in 1983, 9 years after the CSA signed the Canadarm contract. This initiated the first Canadian astronaut corp. Canada has had 14 astronauts flying with the Shuttle program and the Soyuz program since then, including Chris Hadfield, who served as the ISS Commander in 2013. The Canadian astronauts train and fly with the NASA astronaut corp. The NASA-CSA MoU specifies that during the ISS assembly and verification, fully trained CSA crew members will participate in on-orbit assembly and system verification of the CSA-provided flight elements, such as the Canadarm, as well as for utilization activities. Crew allocation time was initially set at 2.3%.

**European:**
The ESA astronaut corp is selected based on budgetary contributions to the specific programs in which
the astronauts would fly, specifically, contributions from ESA’s member countries. As described earlier, the top contributing countries, Germany, France, and Italy have the most astronaut’s who have flown on the ISS. Interestingly, although Germany contributes the most specifically to human spaceflight, it is Italy who has flown the most astronauts, and France, who reported no budgetary contribution to human spaceflight in 2018 has flown more astronauts than Germany as well. This may be indicative of changing priorities of these countries over the lifetime of the ISS. ESA allocation rights of the ISS were signed at 8.3% of the Station utilisation resources and 8.3$ of crew time, which is approximately 13 hours per week. They have a barter agreement with NASA to use 51% of the Columbus Laboratory in exchange for transportation services.

2.3 Implications

We can draw several conclusions from our case studies. International investments, while not the majority of funding for human spaceflight, still provides invaluable contributions to NASA’s programs. This may be in the form of technology developments, such as the Canadarm, infrastructure for broad use, such as the Deep Space Communications Complex or from expansion of current programs, such as ESA’s Columbus module on the ISS. It is also clear that these agencies are keen to contribute to the changing programs of human spaceflight. Currently, those interests are focused on Lunar Gateway and Orion. This is of some concern given NASA’s policy is refocusing on the Moon to Mars Artemis program and removing the need for many of the commitments that these international partners have made. We discuss this further in the following sections.

In examining the various astronaut programs it is clear that although the primary source for astronaut invitations is based on agreements made on a program by program basis, with monetary equivalent contributions being the main impacting factor, there are likely also political influences on these decisions as well. Looking at the MoU described percentage breakdowns of crew time for the ISS, we can see how this has changed over time, Table 4 compares the 1998 agreed breakdown to the current breakdown. Non-partner countries who have flown must also be considered here as they will have replaced crew which were assigned to other partners. Regardless, it is clear this is an evolving process where agreements must be amended to fit the need.

Table 4: List of major contributions from top participating countries on the ISS program

<table>
<thead>
<tr>
<th>Partner Agency</th>
<th>MoU Agreed %</th>
<th>Current Flown %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roscosmos</td>
<td>50</td>
<td>20</td>
</tr>
<tr>
<td>CSA</td>
<td>1.2</td>
<td>3.3</td>
</tr>
<tr>
<td>ESA</td>
<td>4.2</td>
<td>7.5</td>
</tr>
<tr>
<td>JAXA</td>
<td>6.4</td>
<td>3.8</td>
</tr>
<tr>
<td>NASA</td>
<td>38.3</td>
<td>62.9</td>
</tr>
<tr>
<td>Non-partner</td>
<td>N/A</td>
<td>2.5</td>
</tr>
</tbody>
</table>

3 Future International Involvement

3.1 Artemis Policy Changes

Although many of NASA’s international partners primary interest seems to lie in the Lunar Gateway and a sustained lunar presence, it is apt to examine the necessity of Gateway. And if it is not the best option, then how can these partnerships be protected?

Should NASA’s goals shift away from Gateway and a sustained lunar presence, NASA’s response to international collaborators will need to take into account these partners human spaceflight, exploration and science goals. One such consideration was provided by Dr. Dava Newman during a meeting with the German Space Agency, DLR, at the International Aeronautical Congress in 2015 in response to NASA’s human lunar surface activities:

If our partners want to lead crewed missions to the lunar surface as part of our collaborative activities in cis-lunar space, NASA will support those efforts, but our focus is on buying down risks for the human Journey to Mars in cis-lunar space.

Here we briefly assess some of the pros and cons of the Lunar Gateway and make a recommendation for how our Case Study partners could be addressed.
3.1.1 Lunar Gateway Pros

Originally conceived as an intermediate outpost to test technologies for Mars or an asteroid visit, the Lunar Gateway has had a number of iterations over the years. Current proposals by Congress advocate for a removal of Lunar Gateway from the critical path to Mars, nevertheless there are some distinct technological and political advantages to the building of a sustained lunar outpost.

NASA currently has plans for humans to reach Mars in the 2030s, which requires significant technological developments in a number of areas including life support systems, radiation shielding, in-situ resource utilisation, and crew health. The Lunar Gateway is an ideal proving ground for these technologies, operating at a relatively ‘safe’ and ‘close’ distance to Earth in terms of communications and rescue, but allowing for simulation of Mars-like mission conditions. The Gateway offers the opportunity to test new technologies such as electric propulsion, without the interference of Earth’s gravitational or magnetic field.

NASA continues to move forward with the development and testing of the Orion capsule, and a service module provided by ESA. This craft was originally designed to reach LEO and rendezvous with an upper stage to reach the Moon. Without redesigns, Orion lacks the propulsion capability to reach a lunar orbit capable of supporting a reusable lander. Lunar Gateway provides a base of operations that is more easily accessible by Orion, as well as a place to refuel, or return to and wait for rescue should anything mission critical fail.

From a political perspective, the Lunar Gateway could have a similar economic impact to that of the ISS or the SLS, in creating a significant number of US jobs over several years given the time-frame of the project. From an international perspective, Gateway offers a similar opportunity to that of the ISS. With the ISS scheduled for retirement in 2024, Lunar Gateway would be a new opportunity for international collaboration on a similar scale. A number of agencies (ESA, JAXA, CSA) have committed to developing components for Gateway, thereby offsetting costs for the U.S. Figure 4 shows the proposed international partnerships.

![Gateway Configuration Concept](image)

Figure 4: Illustration of the Lunar Gateway showing the proposed international partner contributions

3.1.2 Lunar Gateway Cons

If the Gateway program moves forward, it will likely follow the political reality in which the ISS, Orion and SLS exist – meaning, these programs have created many good jobs in states and districts of powerful members of congress, making it very difficult to end any of these programs. As with the ISS, the Gateway could become an area of stagnation, limiting the potential to move away from cis-lunar space and progress to Mars. Another limitation of the Gateway is its dependence on Orion and SLS. Both of these programs were designed for the Constellation program, cancelled in 2008, which was intended to be a more Apollo-like lunar landing mission. This means that many of the technical designs of the Orion and SLS limit the mass budgets needed to transport components of Gateway. Further, this limits the orbit selection for Gateway, requiring it to be in a Near Rectilinear Halo Orbit, which may not be the ideal choice for lunar landings. As significant new capabilities emerge in the private industry, such as SpaceX’s Crew Dragon, alternative options can be considered for lunar
missions as well. These new capabilities offer alternatives for some of the arguments for Gateway, such as, if there is no station to return to in orbit then the ascent stage and crew cabin will need to be expendable, or that Gateway could provide a refuelling platform necessary for reusable lunar landers. Using this quickly developing industry technology would eliminate some of these necessities for the Gateway while also dramatically reducing the cost of lunar missions (For reference, a seat on SpaceX’s Crew Dragon is priced at $55 million, while on the SLS/Orion it will be $90 million per seat).

3.1.3 Implications for Case Study Partners

The multilateral agreements made to establish the ISS offered a platform for nations to come together to form a truly collaborative multi-nation habitation in space. We believe that the Gateway could provide a similar opportunity to renew this effort. Notwithstanding the key technologies that would be developed enabling human spaceflight to proceed to Mars, it would allow for a long-term base of shared operations in space. As we become a space-faring planet, these are the steps which develop the foundational policies and agreements that will follow us to the moon, Mars and beyond. As the ISS transitions to private operations, governments must establish their next stages of space habitation as well. While Mars is the ultimate exploration goal, a new headquarters is needed for these deep-space missions to succeed.

Should the Gateway program be cancelled, however, there are avenues in which NASA’s international partners could direct their funding to maintain both their commitments to the Moon to Mars program (currently in the Gateway), but also to maintain a position in which to negotiate astronaut participation.

For Canada, their expertise are currently in robotics, both through the Canadarm and in rover technology, however, they’re most recent commitments also suggested interest in expanding their expertise into biological research, such as radiation protection. Just as the Canadarm was first applied on the Shuttle program, the technology could be adapted for lander applications, or fuel docking stations. As well, encouragement to expand their current work in radiation protection would provide two key contributions to manned mission programs. ESA, while big proponents of the Moon Village concept, have also shown interest in applying for lunar lander contracts. Italy has budgeted €35 million to enter a first contract for a NASA lunar lander should there be a successful outcome of a call to open to foreign companies. This would be of particular interest to NASA as the Italian funding would be redirected from the financing of activities relating to the creation of modules for the Chinese space station. The funds would be for pre-feasibility studies for Modules and Lunar Systems as part of the Italian participation in the NASA Artemis mission. Finally, Australia’s commitments to Gateway have yet to be formalized and could be formatted for a Moon to Mars program. Specifically, as their expertise lie in Deep Space Communications and start-ups, they could be encouraged to provide the communications technologies required for the Mars missions, as well as funding their start-ups to apply for the public-private partnership agreements which are growing quickly in all NASA programs.

Although we have provided solutions for policy changes relating to the cancellation of Gateway, this would require careful individual negotiation to maintain the confidence these partners have in NASA’s programs. Given the dependence of NASA’s programs on administration change, and the associated history of program cancellations, it is critical as we embark on this next phase of exploration that NASA is viewed as a consistent leader in these efforts. With the growth of other international agencies and their development of human program capabilities, a shift in the outlook of NASA’s programs could result in many of their international partners joining with more stable programs whose goals more strongly reflect their own.

4 Policy Recommendations

Taking into account the historical perspective, international contributions, commitments and goals, as well as assessments of future policy changes, we provide here a list of policy recommendations going forward for NASA’s human spaceflight initiatives.

• Potential to transfer the Lunar Gateway to Private and International partners to maintain continued lunar presence
• Consideration of relationship longevity and commitment to NASA in the astronaut selection process (Case Study: Australia was one of NASA’s first international partners and yet has no astronaut invitation).

• Changes to ‘no-exchange-of-funds’ policy regarding deep space international collaborations. Program longevity is often the key downfall of international partnerships, as exploration goals change with each administration, and it’s difficult to build meaningful international collaborations on short time scales with no financial commitment.

• One of the biggest policy recommendations that would support improved International Collaborations is extending the NASA budget beyond a year. With changing administrations, overarching human exploration goals for NASA are constantly in flux, making it difficult for international partners to significantly commit, or be willing to commit, to goals which may change with the next administration. A budget laid out over a greater number of years would lock NASA’s human exploration goals into a 5-10 year timeline.

• In the event of the cancellation of the Lunar Gateway program, reorient international participation to appropriately relevant Mars-mission investments. This would need to take into account the country’s expertise and main areas of interest.

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EXECUTIVE SUMMARY

In-crisis and post-crisis policy making at the age of COVID-19: How the space industry should respond

Because of its importance for Science and Technology, because of its role in the Defense industry and because of the fragility of some of its most promising programs and businesses, the health of the space sector - after that of the people - should be of special concern for governments today. Policymakers have a considerable responsibility regarding how well the industry will get through the crisis.

In-crisis policy making and leadership: “Respond” and “Recover”

What both public and private leadership face today is actually a tradeoff between collaborators’ security and company productivity or accomplishments. It is thus a tradeoff that this industry knows particularly well. The benefit to work continuity could be to deliver a $2.5B scientific program to Mars, or it could be avoiding a few months delay in a non-critical television broadcast satellite launch: there is thus no universal answer. This should be the first priority for industry leaders today: transparency with collaborators about what “maintaining the activity” actually means.

While communicating on this vision is absolutely necessary, sharing an action plan for the months ahead - however reassuring it might be - is probably too ambitious in such uncertain times. At most, and this is our suggestion, guidelines and a response framework should be shared, like NASA did with its 4-stages response framework regarding centers access, health & safety, meetings & events, and travel. Only local decisions both in time and space are flexible enough to face an epidemic with long delays between contagion and testing.

Finally, fast and accurate information is probably the last key element for an effective “Response” in these circumstances. Industry leaders and policymakers should gather expert teams of scientists and physicians to include scenarios and models in the process.

With regard now to the “Recovery” process, making sure that this global pandemic is over as soon as possible is probably the simplest way for the space industry to avoid a long and painful one. Several companies and agencies showed great leadership in the past few weeks by contributing proactively to the effort against COVID-19 (see details in the full report about SpaceX, Virgin Orbit, JPL, Glenn and others). The use of space-based services to help contain the epidemic is also very effective, in particular geotracking through satellites.

Ensuring that every stakeholder will indeed recover at some point is probably too ambitious, but we should make sure that the sector will not wake up next year deprived of its most promising players. In the past five years, the number of space startups emerging has skyrocketed, and for these reasons, many analysts have recently declared that the cleanup resulting from the current crisis would actually be beneficial to the sector. We argue that this is an error of judgement, and a potentially dramatic one. In a “Darwinistic” approach of business, an accelerated “survival of the fittest” period could have its advantage, for sure. But when the game is rigged, the final players probably won’t be the ones the world needs the most. This game is rigged because startups that just raised funds have a full runway to survive the crisis, while startups planning to raise in the coming months will struggle to find investors and may run out of cash.

Public actors such as the AirForce and agencies are and should continue being active to fund and invest in promising startups in the coming months. The most affected segments will probably be LEO satellite constellations and small launchers: the most capital-intensive segments. Chair of the Space Acquisition Council Dr. Roper declared he was working on options to bring economic stimuli to
aerospace startups. DoD also injected $3B dollar in accelerated payments to their network of startups and small businesses.

We also want to mention that preparing for what’s next also includes making the most out of the few opportunities this crisis offers. The space industry is of course very involved in the fight against climate change and measurements conducted today could help fine tune our models. In particular, it could help research distinguish human impact from natural sources of greenhouse gases.

How did the industry actually respond to the crisis? Strategies have been very diverse depending on the country and the level of urgency of current programs, we invite you to read the report for a detailed picture.

Post-crisis policy making and leadership

Economic recession is synonymous with reluctance to capital-intensive investments, and this will be an issue for the space industry more than any other. The fall of OneWeb was multifactorial, but others will follow. This phenomenon may boost the development of on-orbit servicing, to extend the lifetime of existing space systems instead of replacing them.

The likely massive economic stimulus that will follow the crisis is an obvious occasion for reorienting investments in the right direction, and this is also true for the space industry: sustainable debris mitigation projects, climate monitoring systems, etc.

Investments in space science and technologies may be affected too, but not necessarily in the way we imagine: the rising tensions with China may lead to increases in funding. Space exploration and the Artemis program in particular may gain in popularity in the Congress. We believe that Artemis should not be a 2nd 1969, but rather put as a priority the international cooperation behind the US leadership, to ensure a sustainable presence on and around the Moon, as a first step towards Mars.

Review of the main recommendations

- Respond to crises innovatively
- Leverage new crisis management protocols
- Foster international collaboration & analysis sharing
- Use multi-disciplinary approaches & Collaborate with private partners
- Detect emerging risks with horizon scanning and forward looking
- Crisis identification / monitoring: role of expertise
- Use strategic crisis management training to learn agility and adaptability
- Management of large-response networks
- Use crisis as an opportunity for change & organizational restructuring

Specific to the space sector:

- Transparency about what “maintaining the activity” actually means
- Rely on local policies (both in time and space) as much as possible
- Secure leadership access to fast, accurate information and models
- Leverage space technologies and experts in the global effort against COVID-19
- Foster public funding for aerospace startups (“survival of the fittest” will not be efficient)
- Favor extending the lifetime of existing space systems over replacing them
- Economic stimulus will be an opportunity to promote sustainable approaches
- Rising tensions with China may lead to an increase in funding for strategic space technologies, but Artemis should keep as a priority the international cooperation
In-crisis and post-crisis policy making at the age of COVID-19: how the space industry should respond

Elwyn Sirieys & Heng Zuo
May 2020

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"Things fall apart; the center cannot hold."

William Butler Yeats coined this phrase a century ago in his poem “The Second Coming” [1], describing a world spinning out of control as chaos reigned in the aftermath of the First World War.

Today, it seems apt as ever.
1. Introduction: Overview of policy responses to COVID-19

During the first months of 2020, most countries in the world have been progressively affected by a new coronavirus called SARS-CoV-2, responsible for the COVID-19 disease. To this date, 4.2M people have been officially tested positive (JHU), including 1.4M in the US, 230,000 in Spain and 220,000 in Italy. Among this probably highly underestimated number of cases, more than 280,000 have died. Facing such a tragedy, unprecedented for the past century, countries and industries have had extremely diverse responses and policies, depending notably on their cultures, political regimes and preparedness.

**Figure. 0**: John Hopkins University Live Dashboard of the COVID-19 situation.

1.1. Public policy: Government responses

Today, the majority of the governments in the world have recommended similar responses — a combination of both pharmaceutical and nonpharmaceutical interventions. The former mainly includes aggressive and massive testing, the race of development of new test kits, the extensive research on effective drugs and vaccines, and the construction of field hospitals and deployment of medical practitioners to the epidemic center, etc. The nonpharmaceutical interventions, also known as community mitigation strategies, such as proper social distancing, quarantine and isolating infected citizens from the general population, encouraging the practice of wearing masks, and even travel restrictions, are used to help slow the spread of the pandemic.

Many governments take steps to address the importance of informing the public with open communication and information sharing. Other commonly implemented strategies include using contact tracing, GPS tracking, surveillance, issuance of “health codes”, etc. to track the spread of the pandemic. Governments around the world also act decisively to protect the businesses and people from the economic disruption, including using tax cuts, investment incentives, economic stimulus for hard hit industries, to alleviate the financial and economic turmoil caused by the pandemic.
The section only lists a number of relatively distinctive approaches used by different countries. Asia, where the pandemic first broke out, has provided many examples of policies that worked—from China’s speedy hospital construction to South Korea’s aggressive testing to Singapore’s contact tracing and open public communication.

China first started a series of quarantines to reduce the risk of human-to-human transmission, from city level all the way up to national level lockdown, starting from the eve of the week-long Chinese New Year holiday. Two emergency specialty field hospitals were constructed near city Wuhan in just days, and later on a number of makeshift hospitals for large-scale medical isolation were adapted through the acquisition of existing venues. Extensive surveillance has also been deployed to control the spread of the virus. A new app — Alipay Health Code, is developed by a tech giant which would assign users a rating of green, yellow, or red, based on their personal health records with the company.

South Korea takes a strategy to test as many people as possible in the hope to cut off the source of infection. Local medical companies worked together to develop new kits and rolled them out aggressively, allowing government planners to keep track of the pandemic’s spread. They took lessons learned from the 2015 MERS outbreak and developed drive-through testing sites that help to reduce testing time and protect medical staff. They implement apps which will notify officials if a diagnosed person has left their home and tap into their GPS data to pinpoint their location histories. They also created apps to display available masks at nearby locations to prevent citizens from lining up at pharmacies.

The US federal government has declared states of emergency, and created a website listing all government responses to COVID-19 to inform the public from federal agencies on how they’re responding to the coronavirus pandemic.[39] In response to the pandemic, new fiscal and monetary policies have been issued, including a $484 billion Paycheck Protection Program and Health Care Enhancement Act, an estimated $2.3 trillion Coronavirus Aid, Relief and Economy Security Act, an $8.3 billion Coronavirus Preparedness and Response Supplemental Appropriations Act and $192 billion Families First Coronavirus Response Act. [40] In addition, each state manages its own response to the pandemic.

Overall, in the absence of effective drugs or vaccines for this new infectious disease of high transmission, the aggressive disease containment efforts in governments all over the world have considerably changed the course of the Covid-19 outbreak.

1.2. Corporate policy: Industry responses

Private companies and research institutes around the world have worked with governments to develop various coronavirus tracking apps with distinctive features. A team led by MIT researchers also developed technology to use short-range Bluetooth signals emitted from people’s smartphones to trace who they’ve been in contact with and automate the Covid-19 contact tracing while preserving privacy. [49]

Similarly, in a new project slated for release in May, the smartphone operating system rivals Apple and Google are jointly building a COVID-19 tracking tool that makes no use of the
location data into iPhone and Android devices, to help track the spread of coronavirus based on proximity to other phones. The software allows iOS and Android users -- which accounts for 99% of smartphones -- to voluntarily share data through Bluetooth transmissions and health organization approved apps, and users will be informed if they have been in contact with an infected person.[50]

Despite facing severe operational and financial challenges, most companies comply with the governmental social distancing policy recommendations and have adjusted their hours of operation as well as issued their own remote working policies in protection of their employees. At the same time, many corporations begin to compile their resources and start projects to help ease the community’s suffering and develop solutions for the pandemic. Many of them have already stepped up to support their workers, customers, and local communities. Data shows that among America’s 100 largest public employers, 62% of them are engaged in community services, 64% issued customer accommodations, and 60% of them have offered production, distribution, or logistical support amid the crisis.[47]

Carmakers and spacefaring companies, capable of reallocating production and research capacities, are changing tack to support doctors, care facilities and refugees globally. World’s leading 3D printing manufacturers, including HP, Johnson & Johnson, General Electric, Royal DSM and others, have come together to address equipment shortages and rising medical demands due to the ongoing pandemic by providing ventilators, masks, swabs, face shields and more.[52] Engineers at several space companies — including SpaceX, Virgin Orbit and Blue Origin — have started working on medical devices and protective equipment in response to shortages in hospitals as well. Virgin Orbit designed a simplified ventilator at its rocket factory in Long Beach, CA, and SpaceX has agreed to supply ventilator valves for the medical supply company Medtronic.[53]

MGH, Harvard Medical School, and a few other research institutes have collaborated to develop a COVID-19 Simulator, to help policy makers decide how to respond to the novel pandemic. By modeling the impact of different social-distancing interventions on reduction in the spread of coronavirus across different US states, the simulator presented information to help policymakers understand consequences such as the rate of new cases, potential strain on the healthcare system, and projected deaths. [41]

In the “Community Mobility Reports”, Google uses their location data to show how various communities are moving around differently due to COVID-19, therefore indicating the level of compliance to the stay-at-home orders. By charting movement trends over time by geography, across different categories of places such as retail and recreation, groceries and pharmacies, parks, transit stations, workplaces, and residential, the reports provide insights for policy makers as they make critical decisions aimed at combating the pandemic.[42]

Another project created out of Google’s X Lab -- Alphabet’s Wing, is a drone delivery test project approved by the FAA, which has been offering groceries, medicines, and even pastries deliveries to the town of Christiansburg, VA, since last October. After the stay-at-home order
went into effect, demand for its drone-delivery service has surged dramatically, which may accelerate the mainstream adoption of this futuristic service.[51]

2. Background & Literature Review

2.1. Crisis management framework

Crisis management is the process by which an organization deals with disruptive and unexpected events.[2] Originated in the large-scale industrial and environmental disasters since the 1980s, crisis management is considered to be one of the most important processes in public relations.[3] Within the broader context of management, this discipline consists of skills and techniques to identify, assess, and cope with serious situations before, during, and after they have occurred, especially from the moment it first occurs to the point that recovery procedures start.

The three common elements to a crisis include: (a) a threat to the organization or its stakeholders, (b) the element of surprise, and (c) a short decision time.[4] Crises disrupt people and communities, damage organization reputations, and cost enormous amounts of money. In addition, they can serve as the impetus for investigations and organizational change, where Venette et al. have argued that "crisis is a process of transformation where the old system can no longer be maintained".[5] Therefore, the need for change is the fourth defining quality for a crisis.

Crisis management is situation-based and it includes clear roles and responsibilities. The response includes actions in several stages, from crisis prevention, assessment, handling to termination. Failure to respond to the crisis can result in losses for an organization and serious harm to stakeholders. So building a knowledge of crisis management and having a set of best practices would be a very useful resource.

There has been a dynamic and growing body of communication and organizational literature that explores multiple aspects to deal with crisis, including various developmental approaches to describe crisis, decision making, public relations, rhetorical approaches, organizational legitimacy, and methodologies for crisis communication research.[6] Both practitioners and researchers from many different disciplines have written about crisis management and created protocols when faced with crises. For example, the Federal Emergency Management Agency (FEMA) was established on April 1, 1979 by President Jimmy Carter, with the mission to lead America to prepare for, prevent, respond to and recover from disasters with a vision of "A Nation Prepared."[7] It has developed strategies to coordinate the response to a disaster that has occurred in the United States which overwhelms the resources of local and state authorities. Many other governments and agencies around the world have their own version of crisis management strategies. However, the crises we have now have continued to evolve and challenge even the most recent and robust systems.
New nature of crisis in an interconnected world

As our societies are becoming more complex and interconnected, as well as increasingly vulnerable and exposed, new threats can emerge and spread more quickly through spill-over or amplifier effects. In recent times, governments are facing an increasing number of crises, often consisting of new threats, which may spread beyond national borders and create significant effects to the global economy. In the wake of crises, global leaders need to stay aware of any further systemic shocks that could severely challenge economic recovery, social cohesion and even political stability. And citizens’ trust in governments is directly affected by how swiftly and efficiently governments can react in crises.

The complexities of modern crises call for effective coordination to ensure a successful outcome, as many actors are involved, beyond emergency services. The coordination poses significant challenges to public governance, with many crisis management exercised at sub-national levels and coordinated at the centres of governments. The ability to coordinate crisis management tests governments’ capacity to provide the appropriate responses properly, to protect the citizens and businesses and mitigate the impact of crises. Therefore, it is critical to ensure an institutional framework for national authorities to provide them with the right tools for co-ordinated actions.

Many recent crises have challenged political leadership around the world, caused by the unexpected or unforeseen nature of the circumstances, and weak links in the information flow. Looking back at the events of 11 September 2001, the SARS and H1N1 pandemic outbreaks in 2003 and 2009, or the 2011 Tohoku earthquake and tsunami in eastern Japan, which resulted in cascade effects of the Fukushima Daiichi nuclear accident, during which many risk managers, processes and structures were unprepared to deal with. These new crises share many new signatures:

- Unexpectedly large scale,
- New or unprecedented -- at least in human or crisis managers’ memories -- or their unusual combination,
- Trans-boundary nature [7].

The last term refers to the fact that many of these crises spread across geographic borders or policy boundaries -- between nations, States or other local authorities and between administrations, sectors, public-private etc. They bring deep uncertainties and challenge government structures, and create tensions between many stakeholders in the public and private sectors.

Different approaches in crisis management

These new features of crises require governments to adapt their approaches in various aspects of crisis management towards more flexibility. Baubion et al. discusses several approaches and practices in dealing with both traditional and novel crises, which lay out possible pathways that governments can adapt to changes while maintaining capabilities to deal with various crises.
### TABLE.1 Different approaches in crisis management: traditional crisis management vs. dealing with novelty [6]

<table>
<thead>
<tr>
<th>PREPAREDNESS PHASE</th>
<th>Traditional crisis management</th>
<th>Dealing with novelty</th>
</tr>
</thead>
<tbody>
<tr>
<td>● Risk assessment based on historical events</td>
<td>● Risk assessment includes horizon scanning, risk radars and forward looking analysis to detect emerging threats.</td>
<td></td>
</tr>
<tr>
<td>● Scenario based emergency planning</td>
<td>● Frequent updates and different time-scales, international analysis sharing, multi-disciplinary approaches</td>
<td></td>
</tr>
<tr>
<td>● Training to test plans and procedures</td>
<td>● Capability-based planning and network building</td>
<td></td>
</tr>
<tr>
<td>● Early Warning Systems based on monitoring, forecasting, warning messages, communication and link with emergency response</td>
<td>● Strategic crisis management training to learn agility and adaptability and create networks and partnerships</td>
<td></td>
</tr>
<tr>
<td>● Strategic crisis management training to learn agility and adaptability and create networks and partnerships</td>
<td>● Strategic engagement from centres of government</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>RESPONSE PHASE</th>
<th>Traditional crisis management</th>
<th>Dealing with novelty</th>
</tr>
</thead>
<tbody>
<tr>
<td>● Command and control system</td>
<td>● Crisis identification / monitoring: role of expertise</td>
<td></td>
</tr>
<tr>
<td>● Standard Operating Procedures (SOP)</td>
<td>● Flexible and multi-purpose crisis management teams and facilities</td>
<td></td>
</tr>
<tr>
<td>● Strict lines of responsibilities</td>
<td>● Common concepts across agencies to inform leadership with high adaptive capacities</td>
<td></td>
</tr>
<tr>
<td>● Sectoral approaches</td>
<td>● Similar tools and protocols that could be utilised for multi-crisis</td>
<td></td>
</tr>
<tr>
<td>● Principle of subsidiarity</td>
<td>● International co-operation</td>
<td></td>
</tr>
<tr>
<td>● Feedback to improve SOPs</td>
<td>● Management of large-response networks</td>
<td></td>
</tr>
<tr>
<td>● Feedback</td>
<td>● Ending crisis and restoring trust</td>
<td></td>
</tr>
<tr>
<td>● Feedback</td>
<td></td>
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</tbody>
</table>

### Crisis leadership

Crisis leadership research finds that leadership actions in crisis reflect the competency of an organization, since the crisis tests how well an organization’s leadership structure serves its goals and withstands crisis. James and Wooten[10] identify six leadership competencies which promote organizational change and restructuring during and after a crisis including:

- Building a foundation of trust
Reforming the organization’s mindset
Identifying obvious and obscure vulnerabilities of the organization
Making wise and rapid decisions
Taking courageous actions
Learning from crisis to effect change.

A leadership approach to crisis management calls for investment of time, energy and resources. It requires leaders to change the way they think about and respond to crisis situations in turbulent environments.

2.2. Upheaval: How nations cope with crisis and change -- An analogy to how individuals cope with personal traumas

Apart from the above protocols, some historians have studied the real-world examples of devastating crises (political, economic, civil, ecological, etc.) in the past that may destroy whole countries and the multiple reasons causing them. In a book Upheaval: How Nations Cope with Crisis and Change[9], Jared Diamond investigates the past crises that have hit such countries as Finland, Japan, Chile, Indonesia, Germany, Australia and the United States, by looking at how these countries faced past upheavals at pivotal moments in their histories with self-appraisal and adaptation. By tracking through Finland’s World War II-era conflict with the Soviet Union, Japan’s path toward modern stability since the Meiji-era, Chile’s political polarization and struggle under dictatorship, Indonesia’s rise to self-determination from colonialism, Germany’s rebuilding and rebranding after the Nazi era, and Australia’s rise to a diverse nation, Diamond describes how these immensely different geographical countries either overcame their challenges or rather studiously avoided doing so.

The historian examines the ways in which individuals learn to cope with personal traumas and how these approaches can be applied to nations as well. Unexpectedly, he concludes that individuals do learn from crisis, but countries seldom do. Therefore, he makes an erudite case for learning from history and applying its lessons to our global future. Whether a crisis is gradual or immediate, personal or national, it requires selective changes and the examination of a number of factors that often contribute to finding a solution, analogous to personal therapeutic strategy:

- Acknowledging the crisis itself
- Accepting responsibility to respond to crisis
- Selective change -- distinguishing the things that need to change from those that are so important to the identity that shouldn’t be interfered with
- Getting assistance from outside resources
- Learning about the methods others have used to respond to similar crises
- Recognizing a personal or national identity
- Undertaking an honest self-appraisal
- Recognizing and learning from how past crises have been handled
- Showing patience in coping with failure
- Showing flexibility
2.3. The Role of Scientists and Experts

A particularly sensitive aspect we wanted to address here is the position of experts in the decision making process, especially in the case of public policy. Many questions faced by governments in the past few weeks have highlighted the need for efficient interactions between public leaders and scientists: test and use of new drugs, lockdown policies, Personal Protection Equipment (PPE) use by the population (not just physicians), among others. Here we decided to rely on the case of Hydroxychloroquine (HCL) to show the dramatic consequences of an ill functioning relationship between both worlds and how to improve the relationship through a well accepted framework.

HCL, which is a very cheap drug used mainly against malaria and arthritis, has recently been approved by the U.S. FDA (Food and Drug Administration) against COVID-19. In France, where the drug is being tested by a loud and controversial doctor in Marseille (Pr. Didier Raoult), the understandable impatience from the public and the government for a “miracle drug” has led the debate out of the scientific sphere. Like most active substances, it has side effects, and in this case risks of cecity and cardiovascular problems. Its effects against COVID-19 have been demonstrated on cells in laboratories, but not yet on human beings (most studies are inconclusive or highly contested in their methodology).

Is HCL or a combination of HCL and other medicines active against COVID-19? Do the benefits of HCL outweigh the side effects? Should HCL be given to anyone suspected of being infected with COVID-19? These are inherently scientific questions that should ideally be answered by scientists before being shown. Prof. Didier Raoult broke the frontier of the scientific sphere in February and directly reached out to the people, on social media and on YouTube. Now HCL has become a political topic. Some people “believe” in it, some don’t. Now people with no understanding whatsoever of what it is really about do weigh in the fight to force the French government to “admit” its effectiveness and start using it. A similar issue appeared in the US with two protagonists: President Donald Trump and Director of the National Institute of Allergy and Infectious Diseases (NIAID) Anthony S. Fauci.

People will never be to blame, especially in these circumstances where simultaneity between the fear of an indefinite threat and the discovery of a possible cure by supposedly credible experts generates such hope. But some scientists and politics will be if the pressure is high enough to push the government to take an early decision. For now, President Macron only has
authorized the use of HCL for dramatic cases, but a few physicians use it for anyone who asks, in Marseille for instance.

While there is no relevance in any political or public opinion regarding the questions above, every stakeholder should be aware of the limits of the scientific domain. Is HCL effective against COVID-19? This is a scientific question. Should HCL be used tomorrow in Hospitals against COVID-19 despite the risks? These are questions for public policy experts and for people's representatives, not for scientists.

So, how should we think about the use of Science and Experts for policy matters? There is not a single way for scientists to be involved in the policy-making process and society benefits from a diversity of these roles. Roger A. Pielkem Jr offers a well-known framework to answer this question (Figure 1).

<table>
<thead>
<tr>
<th>View of science</th>
<th>Pure Scientist</th>
<th>Issue Advocate</th>
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<td>Linear model</td>
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<td>Stakeholder model</td>
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<td>Schattschneider</td>
<td>Science Arbiter</td>
<td>Honest Broker of Policy Alternative</td>
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**Figure. 1:** Framework for the study of Scientists’ roles in Society. Roger A. Pielkem Jr., The Honest Broker, making sense of science in policy and politics [55]

Pielke distinguishes four different roles for Scientists in the process: “Pure Scientists” provide basic consensus information unbiased by policy making motives, “Science Arbiters” provide the same scientific information but from a policy perspective, “Issue Advocates” argue for particular outcomes and reduce the scope of choice, and finally “Honest Brokers of policy alternatives” provide relevant scientific information for decision makers to clarify the landscape of policy options available.

What we need today, in such a fast changing context with urgent matters to solve on a global scale, are “Honest Brokers of policy alternatives”. Anthony Fauci could probably be classified in this category, for his humility, neutrality, and level of scientific expertise [54]. However, the price is a lack of efficiency dealing with highly politicized leaders: Anthony Fauci cannot advocate for specific policies.
3. Historical comparisons to the 1918 influenza pandemic outbreaks

It has merely taken a few months for the Covid-19 to sweep the globe. As it continues to spread, people wonder how many of us will die and how societies will change, so it’s important to look back at past pandemics and how they have reshaped our societies in profound ways.

Figure 2. Deaths from pandemics, from antiquity to the modern era. [19]

3.1. The 1918 flu pandemic & H1N1

The covid-19 pandemic has inspired lots of comparisons to the 1918 flu pandemic, which was an unusually deadly and the most severe influenza pandemic in recent history. Lasting from spring 1918 through early summer 1919, it infected 500 million people – almost one third of the world’s population at the time, with estimates of 50 million deaths worldwide, according to the CDC.[16]

The pandemic was caused by an H1N1 virus with genes of avian origin. It coincided with World War I, and the conditions of the war such as overcrowding, malnourishment, poor hygiene and global troop movement may have helped spread the flu and promoted bacterial superinfection.[20] The vulnerability of healthy young adults and the lack of vaccines and treatments also exacerbated this public health crisis.[16]

Unlike all previous and subsequent pandemics, the 1918 flu pandemic seems to have spread in at least 3 distinct waves within a 9-month interval.[20] The second wave was much more deadly than the first, with the virus mutated to a much more deadly form,[21] and October 1918 saw the highest fatality rate of the pandemic. A third wave of the flu started in January 1919 and lasted until June 1919, resulting in hundreds of thousands of deaths.[22] In spring 1920 a very minor fourth wave occurred in isolated areas including New York City,[23], with low mortality rates.
3.2. Measures & Efforts

With no vaccine to protect against the flu and no antibiotics to treat secondary bacterial infections associated with influenza infections, control efforts were limited to nonpharmaceutical interventions (NPIs) worldwide. Measures used to slow down transmission, though applied unevenly, include: isolation, quarantine, good personal hygiene, use of disinfectants, and limitations of public gatherings. Getting citizens to comply with such orders was not easy, and in some cases health officers had to fine or shoot people for not wearing mandatory face masks and protective gear in the US.[26] But eventually, the most drastic and sweeping measures paid off.

An invaluable amount of historical data has shown the effects of such measures, which can be used to inform our actions in the new crisis. Several studies have analyzed the health data from the U.S. census that experienced the 1918 pandemic, and charted the death rates of 43 U.S. cities, in order to understand how responses may influence the spread of the virus in different cities. By comparing fatality rates, timing, and public health interventions, they found death rates to be 50 percent lower in cities that implemented preventative measures early on, compared to those that did so late or not at all. This has lessened the strain on health care systems.

Figure 3. How some cities have “flattened the curve” with social distancing and saved thousands of American lives during the pandemic: The efforts and outcomes implemented to stem the 1918 flu’s spread in cities across America. [24]
The efforts and outcomes implemented to stem the flu’s spread in cities across America are shown in Figure 3, which may offer lessons for battling today’s crisis. Cities that responded fastest and most effectively experienced a cut in the transmission rates by 30 to 50 percent. New York City was among the earliest to react to the crisis with mandatory quarantines and staggered business hours, resulting in the lowest death rate on the Eastern seaboard.

Another important conclusion by the studies is that relaxing intervention measures too early could cause an otherwise stabilized city to relapse, resulting in a second wave of high death rates. These findings show a strong association between early, sustained, and layered application of nonpharmaceutical interventions and mitigating the consequences of the 1918 flu pandemic in the US.

### 3.3. Economic impacts

A number of economists have studied the varying policy responses to the 1918 flu pandemic in the US to shed light on the economic effects into physical distancing and forced retrenchment. They find that it was the pandemic itself, not the policy responses, that hurt economic growth.[25] The main findings are summarized in Figure 4, which shows the city-level correlation between 1918 flu mortality and the growth in manufacturing employment from 1914 to 1919 census years. The figure splits cities into those that were more and less aggressive in their use of NPIs. Cities that implemented stricter NPIs (green dots) tend to be clustered in the upper-left region with low mortality and high growth, while cities with more lenient NPIs (red dots) are clustered in the lower-right region with high mortality and low growth.

The conclusions[35] are:

- Areas that were more severely affected by the pandemic saw a sharp and persistent decline in real economic activity, and higher mortality during the flu is associated with a relative decline in economic activity.
- NPIs play a role in attenuating mortality, but without reducing economic activity. Cities that implemented early and extensive nonpharmaceutical interventions suffered no adverse economic effects over the medium term.
- NPIs can have positive effects on the economy, through limiting spikes in infections and avoiding mass casualties, resulting in a relative increase in real economic activity after the pandemic subsided.

Altogether, the suggestion is that despite the substantial economic costs to deal with the pandemics, health interventions help rather than hurting the economy, and nonpharmaceutical interventions can lead to both better economic outcomes and lower mortality rates.
Another research examines the effects of influenza on subsequent economic growth using data on US states for the 1919-30 period.[28] The 1918 flu epidemic had a disproportionate number of victims of men and women ages 15 and 44, leading to extremely high death rates in the prime working ages. By using state-level personal income estimates for 1919-1921 and 1930, and controlling for numerous factors including initial income, density, urbanization, human capital, climate, the sectoral composition of output, geography, and the legacy of slavery, the research found a positive and statistically significant effect of the influenza epidemic on subsequent per capita income growth across different US states during the 1920s.

3.4. Social, cultural & other long-term impacts

Historian Dr. Nancy Bristow looks at the social and cultural history of Americans during the pandemic, and she finds that social identity shaped the experience of the pandemic for most Americans. The flu came as a mystery that confounded medical professionals who were confident about addressing any infectious illness before this epidemic, due to the development of medicine in the late 19th century. The epidemic terribly shocked the medical practitioners as traditional medicine failed in the face of the epidemic, but it was nursing that played the most important role in patient care during the pandemic, in which their primary responsibility was not to cure or to save the sick but caregiving. Therefore, nursing staff celebrated the success of their patient care and did not associate the spread of the disease with their work.[34]

Since most nurses are female, it also became one of the great opportunities as a profession for women at the time. According to Bristow, the success of women in the field of nursing may be credited to the increasing number of women attending college, together with the pandemic.
The first large generation of women who went college in the 1890s became capable of capitalizing on their education, and they gained greater prestige and were paid better for their services and accomplishments.\[34\]

Bristow also argued that “the economic circumstances framed the impact of the disease”. Wealthy people may afford health care, but the poor suffered from a lack of access to the resources of nursing and medicine, which were already thinly spread by the war. They may not get a spot in a hospital bed and could only count on the public clinics that opened. The cases were more severe for the large number of immigrants at that time who didn’t speak English, combined with problems of racism or ethnic discrimination. African American and people in the South may only go to a segregated hospital because emergency hospitals were created by the white community. No consideration was made for the needs of Mexican Americans or people living on reservations.\[34\]

The pandemic also revealed a change in how people comply with government interventions. At the beginning of the pandemic, people were anxious to do as they’re told in the hope and optimism that the power of the expert will protect them. But as the influenza returned to so many communities in the second and third waves, people got weary of the social distancing and public health efforts, and were not convinced by the experts or the government. By the end of the pandemic, Americans began to return to their regular habits regardless of the pandemic, resulting in a massive backlash against government interventions and the authority of experts.

Nevertheless, Bistow concluded that though this major catastrophe disrupted the basic patterns of American life, it did not foster long-term social or cultural change but instead led to a strengthening of the status quo and the disparities of American society. Americans refocused on the future, and the despair of those who suffered during the pandemic slipped from public memory.\[33\]

A study of the data from the 1960–80 decennial U.S. Census indicate that the pandemic has led to other social impacts, including “reduced educational attainment, increased rates of physical disability, lower income, lower socioeconomic status, and higher transfer payments received compared with other birth cohorts.”\[27\] Some evidences suggested that pregnant women exposed to the influenza in 1918 gave birth to children who had greater medical problems later in life, such as schizophrenia, diabetes and stroke. This research indicates that investments in fetal health can increase human capital and productivity.

The global economy suffered from the pandemic, especially the losses in revenue in the entertainment and service industries, yet the healthcare industry has reported profit gains.\[32\]

### 3.5. MIT’s response

The flu also hit MIT in the midst of the development of several war-related programs to prepare soldiers and officers for the U.S. Naval and Army forces in WWI. The Institute was busy building temporary housing and research facilities on the relatively new Cambridge campus, which changed after the declaration of the armistice on Nov. 11, 1918.\[30\] In the
1918 Report of the President[36], a three-week delay was posed in the start of the fall 1918 semester at the request of federal and state authorities "due to prevalence of Spanish Influenza and Grippe which has spread throughout this section of the country." The Tech announced the postponement, saying, "It is our aim to aid in every way possible the fight against this terrible disease which now seems to have passed its crisis."[37]

Contemporary newspaper accounts also showed that MIT complied with emergency governmental regulations of local municipalities, and delayed the opening of a newly constructed mess hall on campus to prevent the congregation of large numbers of people in one space. But MIT worked to maintain academic continuity during the major disruption. In a circular letter from President Richard Maclaurin to the students in the Dec. 21, 1918, issue of The Tech[38], he referred to the "abnormal" conditions of the fall semester by acknowledging that “[the faculty] will not adopt a policy that will involve a lowering of the Institute’s standards,” and noting some of the ways students could catch up to continue their normal academic progress.

These valuable documents provide us with the individual and collective experiences in those extraordinary times, and can be used to help with the decision making and evaluation of the responses to future "abnormal" events.

### 3.6. Implications

Compared to a hundred years ago, considerable advancements have been made in the areas of healthcare technology, disease surveillance, medicines and drugs, vaccines and pandemic management. Flu vaccines are produced and updated yearly, and yearly vaccination is available. Antiviral drugs can treat flu illness, and are used for prophylaxis. Various antibiotics are also available to treat secondary bacterial infections.

However, dramatic demographic shifts during the past century have created increasingly more difficulties to contain a pandemic. The rise of globalization, urbanization, and more densely populated cities can facilitate the spread of a virus across a continent in much shorter time, yet our available responding tools have remained nearly unchanged. Just like then, public health interventions are still the first line of defense against an epidemic in the absence of a vaccine. Therefore, understanding patterns of the past pandemic is important for developing prevention strategies and estimating public health burdens.

The elucidation of this past pandemic carries many future implications, and it should be viewed as a reminder to humanity of the importance of the continuous fight against emerging and reemerging infectious diseases.
4. The case of the Space sector

Space industry leaders - be it from agencies or private companies, from startups or multinationals - face during the current crisis challenges similar in many ways to what we described for the global Economy. We argue that because of its importance for Science and Technology, because of its role in the Defense industry and because of the fragility of some of its most promising programs and businesses, the health of the space sector should be of special concern for governments today. Policymakers, in the United-States and abroad, have a considerable responsibility regarding how well the industry will survive. There is no question that strategic decisions taken today will shape the future of the sector.

In this section, we attempt to assess the state of the space industry in these challenging times and provide stakeholders with insights and ideas on how to respond to the crisis, recover and plan ahead.

4.1. In-crisis policy making and leadership

4.1.1. Managing the crisis: “Respond”

What both public and private leadership face today is a tradeoff between collaborators’ security and company productivity or accomplishments. It is thus a tradeoff that this industry knows particularly well. Human beings are and have to be the first priority in any decision. It should also be noted that there would be no space exploration, no International Space Station (ISS), no Gagarin and no Armstrong with a zero-risk policy. A tremendous benefit for an organization, a nation, or for mankind can indeed tilt the balance.

In the case at hand, the benefit to work continuity could be to deliver a $2.5B scientific program to Mars, or it could be avoiding a few months delay in a non-critical broadcast satellite launch. There is thus no universal answer. This should be the first priority for industry leaders today: be honest with employees about what “maintaining the activity” actually means. Transparency, exemplarity, along with a reminder of what values leaders and employees of an organization together believe in. Because this question won’t be answered by scientific studies or business plans, but require a very different set of criteria.

While communicating on this vision is absolutely necessary, sharing an action plan for the months ahead - however reassuring it might be - is probably too much in such uncertain times. At most, and this is our suggestion, guidelines and a response framework should be shared, like NASA did with its 4-stages response framework regarding centers access, health & safety, meetings & events, and travel (see Figure 5 below). The rest of the time, and from the outset of the crisis until today, day-to-day activity management should be the policy. Only local decisions both in time and space are flexible enough to face an epidemic with large delays between contagion and actual testing. Continuity and stability should be maintained as much as possible, considering the tradeoff exposed above.
Finally, fast and accurate information is probably the last key element for effective decision making in these circumstances. Industry leaders and policymakers should gather expert teams of scientists and physicians to include scenarios and models in the equation. This, along with existing information from official sources (CDC guidance for businesses [11]), resources on crisis management (see part III) and uncertainty management in the space industry [12][13].

In the light of these ideas, now how did the industry actually respond to the crisis? Strategies have been very diverse depending on the country and the level of urgency of current programs. Nasa is now in stage 4, which means that only the required safety and security personnel is allowed on site. NASA Administrator Jim Bridenstine encouraged employees to act at their level if they felt additional steps should be taken: "If you think something is unsafe, don't do it" he declared during a town hall in April, and added "you've got my commitment to continue defending your decisions". NASA also decided to only prioritize two activities: Mars 2020, scheduled for July 17, and the commercial crew program including the launch of the Dragon capsule on May 27. However, Artemis may suffer additional delays as the static fire test of the Space Launch System’s (SLS) is on hold. SpaceX maintained their Starlink launch in April, China National Space Administration (CNSA) is still launching and ISS operations are kept unchanged. On the other hand, two launch providers have decided to stop their launches: Rocket Lab and Arianespace (in French Guiana).

Space activities for Defense purposes have become complex too as analysts must be physically in secured infrastructures to do their work. The geospatial intelligence company BlackSky took the opportunity to offer their telework package “Spectra On-Demand Secure Bundle” to manage sensitive but unclassified information (as reported by SpaceNews [14]). CISA (Cybersecurity and Infrastructure Security agency) provided specific guidance on the critical infrastructure workforce (“Workers who support the essential services required to meet national security commitments to the federal government and U.S. Military, including, but are not limited to, space and aerospace workers [...]”).

**Figure 5. NASA Response Framework, applicable to all NASA civil servants.**
4.1.2. Preparing for what’s next: “Recover”

Making sure that this global pandemic is over as soon as possible is probably the simplest way for the space industry to avoid a long and painful recovery process. Several companies and agencies showed great leadership in the past few weeks by contributing proactively to the effort against COVID-19. Thanks to a reallocation of their production and research capacities, SpaceX is now producing ventilator valves, Virgin Orbit and JPL designed ventilator designs that are simple to manufacture, Armstrong Flight Research Center developed an oxygen helmet, Glenn Research Center is working on a decontamination system called “AMBUS tat” [15]. We already mentioned it before, but the use of space-based services to help contain the epidemic is also very effective, in particular geotracking through satellites. ESA and NASA have also issued calls for proposals to fund ideas that leverage satellite capacities in this context.

Ensuring that every stakeholder will indeed recover at some point is probably too ambitious, but we should make sure that the sector will not wake up next year deprived of its most promising players. Because they are often the most fragile too. In the past five years, the number of space startups emerging has skyrocketed (Figure 6 L), with sometimes hardly realistic projects that require extremely capital-intensive investments. In 2018, an estimated 412 space startups were receiving VC investments and over 500 VCs were investing in space startups for $18B cumulative investments since 2009 (Source:Space Angels [44]).

![Figure 6. New companies created in the space-to-space segment since 2000 (L) - NSR [43]. Public stock performance of the space sector during the COVID-19 crisis (R) - Quilty [46].](image)

For these reasons, many analysts [45] have recently declared that the cleanup resulting from the current crisis would actually be beneficial to the sector. We argue that this is an error of judgement, and a potentially dramatic one. In a “Darwinistic” approach of business, an accelerated “survival of the fittest” period could have its advantages, for sure. But when the game is rigged, the final players probably won’t be the ones the world needs the most. This game is rigged first because startups that just raised funds have a full runway to survive the crisis, while startups planning to raise in the coming months will struggle to find investors and will run out of cash. Second, some segments of the industry are still very young: you wouldn’t put a three-years-old Mohammed Ali into the ring and hope he survives, let him grow and the competition will come soon enough. Public actors such as the AirForce and agencies should be active in the coming months to fund and invest in promising startups. The most affected...
segments will probably be LEO satellite constellations and small launchers: the most capital-intensive segments. Dr. Roper, Assistant Secretary of the Air Force for acquisition, technology and logistics and Chair of the Space Acquisition Council declared being working on options to bring economic stimuli to aerospace startups. DoD injected more than three billion dollar in accelerated payments in the past few months to their network of startups and small businesses. Another resource for small businesses leaders can be found in the CARES act [18].

We also want to mention that preparing for what’s next also includes making the most out of the few opportunities this crisis offers. One of these is offered by the drop in people and companies activity: less transportation, less energy consumption and less production mean less atmospheric pollution. The space industry is of course very involved in the fight against climate change and measurements conducted today could help fine tune our models. In particular, it could help research distinguish human impact on the environment and natural sources of greenhouse gases.

![Figure 7](image)

**Figure 7.** (ESA) “These images, using data from the Copernicus Sentinel-5P satellite, show the average nitrogen dioxide concentrations from 13 March to 13 April 2020, compared to the March-April averaged concentrations from 2019”.

A second opportunity for companies is to speed up their transition to remote operations. Planet, the satellite imagery startup, has already adopted the technology to operate their more than hundred satellites from home. They declared last month “staff members are working from home in full force, including the operational teams needed to maintain stable satellite
operations”. On the other hand, Kubos announced last month that they would offer free of charge their remote control technologies to any satellite operators. Their CEO Marshall Culpepper declared to SpaceNews: “With current technology, there’s no technical reason to require operators to be within visual range of a satellite dish, or even in the same time zone”.

4.2. Post-crisis policy making and leadership

Economic recession is synonymous with reluctance to capital-intensive investments, and this will be an issue for the space industry more than any other. The fall of OneWeb was multifactorial, but others caused by these exceptional circumstances are likely to follow. An economic stimulus would be welcome for the most fragile segments of the sector in 2020/2021, however Space may - understandably - not be in the government’s top priorities. Airlines and tourism suffered far more from the crisis and did not have the support of DoD. Chairman of the House Armed Services Committee Adam Smith declared on April 29 “I don’t think we should put money for DoD in a stimulus package” and added “Any future supplementals should be to fight the virus” (as reported by SpaceNews [31]). We suggest focusing governmental efforts on segments independent from the Defense industry, or neglected by Venture Capital, or promoting sustainable values: debris mitigation projects and climate monitoring systems especially. This phenomenon may also naturally boost technological solutions that aim at extending the lifetime of existing space systems instead of replacing them, such as on-orbit servicing (OOS).

Investments in science and technology may be affected too, but not necessarily in the way we imagine: the rising tensions with China may lead to increases in funding. Space exploration and the Artemis program in particular may gain in popularity on the Hill [48]. We believe however that Artemis should still put as a priority the international cooperation behind the US leadership, to ensure a sustainable presence on and around the Moon, as a first step towards Mars.
5. Conclusion and Policy recommendations

5.1. Crisis Management Suggestions

New forms of crises are calling for new and innovative crisis management responses. This includes leveraging new crisis management protocols, detecting emerging risks with horizon scanning and forward looking, exploring various data mining methods to understand the crisis, managing large-response networks, mobilizing resources at speed and scale, and using strategic crisis management training to learn agility and adaptability of our response system. We also believe that as our world becomes more complex and interconnected, international collaboration, information sharing and open discussion is crucial to the management of any global pandemic. Public-private partnership should continue to be encouraged and pursued, and multi-disciplinary approaches is the key to dealing with any crisis successfully.

By reflecting on and choosing to learn from history, we may be able to avoid the consequences of the return of the ghosts of history. How we have dealt with the previous pandemics should be used as a reminder to humanity of the continuous fight against emerging and reemerging infectious diseases. We should view the crisis as an opportunity for change and organizational restructuring. The future of work and consumption needs to be redefined, and new technology across all aspects of life are to be explored and expanded. After this pandemic, what matters is a new divide between two kinds of countries: those that can plan for the long term, act decisively and invest for the future, and those that cannot.

5.2. Suggestions for the Space Sector

The health of the space sector should be of special concern for governments today for three main reasons: its importance for Science and Technology, its importance for Defense, and the fragility of many of its most promising businesses. Strategic decisions taken today will shape the future of the sector. Industry and agency leaders' transparency with their collaborators about what “maintaining the activity” actually means is crucial, they should rely as much as possible on local policies (both in time and space) guided by global response frameworks and finally secure the access to fast, accurate information and expertise.

Leveraging space technologies and experts in the global effort against COVID-19 has been done already and should continue in the months ahead. Making sure that this global pandemic is over as soon as possible is also the best way to avoid a painful recovery process.

From a business standpoint, both public and private stakeholders should make sure that the sector will not wake up next year deprived of its most promising startups. A brutal period of "survival of the fittest" for companies will not be efficient as the game is rigged. For this reason, we should maintain current risk-taking levels in investments and foster public investment. Economic recession is synonymous with reluctance to capital-intensive investments, and this will be an issue for the space industry more than any other. Economic stimulus would be an opportunity to promote sustainable approaches in space.

Rising tensions with China may lead to an increase in funding for strategic space technologies, but Artemis should keep as a priority the international cooperation behind US leadership.
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