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Benefits Stemming from Space Exploration

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Abstract

Space exploration has produced remarkable advancements in the past decade, marked by a surge in lunar missions, inspiring firsts for nations and businesses alike, growing international and cross-sector collaborations, and expanded opportunities for the commercial sector. As global government funding for space exploration is projected to continue growing over the next decade, effectively communicating the benefits of these investments remains essential for space agencies. Providing transparent, evidence-based rationale for the socioeconomic value of space exploration is key to sustaining public and governmental support for ambitious exploration goals and to fostering a shared understanding of their importance. This paper examines benefits as a foundational rationale for investments in space exploration. It introduces a benefits model developed by the 27 space agencies participating in the International Space Exploration Coordination Group (ISECG) to articulate a unified perspective on the positive socioeconomic impacts of space exploration. The model is structured around 12 benefits, which are defined as quantifiable, positive changes resulting from exploration investments and organized into five categories. They reflect pragmatic and measurable ways in which space exploration drives socioeconomic returns, such as advancements in scientific knowledge, economic growth and enhanced international collaboration. The model also incorporates two cross-cutting themes that capture priorities of sustainable exploration and diversification of actors in the space sector. Leveraging case studies, practical examples and success stories, agency reports and assessments of initiatives, this paper provides insights on concrete positive changes resulting from space exploration for various stakeholder communities. The findings align with ISECG's Global Exploration Roadmap, underscoring the essential role of global partnerships in tackling modern challenges and achieving collective progress in space.

Keywords: Socioeconomic Benefits, International Collaboration, Exploration Roadmap

Acronyms/Abbreviations

International Space Station (ISS), International Space Exploration Coordination Group (ISECG), Global Exploration Strategy (GES), Global Exploration Roadmap (GER), Benefits Tiger Team (BTT), Organisation for Economic Co-operation and Development (OECD), United Nations Office for Outer Space Affairs (UNOOSA), Gross Domestic Product (GDP), LEO (Low Earth Orbit), STEM (Science, Technology, Engineering and Mathematics)

1. Introduction

The history of human space exploration has been driven by tales of resilience and collaboration, scientific breakthroughs, technological advancements, ambition and innovation, and curiosity and wonder. From developing the first satellites and the International Space Station (ISS) to landing human on the Moon and robots on Mars, humanity's exploration of outer space has spurred advancements in all aspects of everyday life on Earth. As humankind writes the next chapter of ambitious exploration, the question of why we explore is just as relevant.

Public and governmental support for exploration is complex. Generally, there is widespread enthusiasm for space. People from all backgrounds and demographics are captivated by the feats of astronauts, innovative space technologies and visions of a future where humans live and work on distant planetary bodies. However, this enthusiasm coexists with doubts about whether the benefits truly justify the costs. Critics of space exploration contend that in the face of global challenges marked by poverty, hunger, and climate crisis, resources might be more effectively allocated to address urgent needs on Earth.

Demonstrating the positive socioeconomic impacts of space is thus key to building robust relationships with policymakers and engaging with the public. Space agencies have long underscored the broader benefits of space, both through official reports on the outcomes of their programs and investments [1-6] and through accessible and relatable communications and resources targeted at the general public [7-8]. These distributed efforts to document the benefits of space are sometimes framed by national priorities and government accountability reporting requirements, and often emphasize the outcomes achieved for their respective constituents. The production of these reports and communications also varies across agencies due to several factors, including government reporting practices, data availability, and resource constraints.

International bodies such as the Organisation for Economic Co-operation and Development (OECD) and the United Nations Office for Outer Space Affairs (UNOOSA) also produce reports, analysis and evidence of the socioeconomic benefits of space investments. These reports offer insights into focused areas such as space economics [9], space sustainability [10], and the contribution of space-based technologies to global development [11]. While these reports speak to the impacts of all space activities, they often have a strong focus on Earth satellite systems, with less emphasis on human and robotic exploration of the Moon, Mars and other destinations in the solar system.

International collaboration in space exploration creates a strong incentive for space agencies to coordinate their messaging on benefits. Despite this incentive, there are few examples of agencies collaborating to articulate a common view on benefits specific to space exploration. ISS Benefits for Humanity [12], a publication co-developed by the ISS international partner agencies, articulates the benefits of the laboratory orbiting in low Earth orbit, but does not introduce a global benefits model for exploration of the Moon, Mars or beyond.

1.1 International Space Exploration Coordination Group

The International Space Exploration Coordination Group (ISECG) was established in response to the Global Exploration Strategy [13], a collective effort initiated by 14 space agencies in 2007 to enhance international collaboration in space exploration; ISECG's membership has since grown to 27 space agencies (Fig. 1). As a voluntary, non-binding forum, ISECG enables space agencies to exchange information, share best practices, and co-develop globally recognized products related to human and robotic exploration beyond Earth orbit. By fostering strategic alignment, ISECG helps its members coordinate exploration objectives, advance scientific and technological collaboration, and articulate a common vision that strengthens public and political support.



Fig. 1. Space agencies participating in ISECG as of April 2025.

As an international coordination mechanism, ISECG establishes working groups and teams to co-develop outputs as needed. The working groups develop non-binding findings, recommendations and publications on topics of common interest to space agencies, with a focus on exploration roadmaps and architectures, science, technology, commercialization, emerging space agencies and benefits.

1.1.1 Global Exploration Roadmap

The Global Exploration Roadmap (GER) [14] is ISECG's flagship product. It is a consensus-driven, non-binding document that outlines a unified vision for

expanding human presence in the solar system through 2050. It outlines shared exploration goals and priorities among ISECG members, emphasizing initiatives in low Earth orbit, sustained lunar exploration, and preparation for future human missions to Mars. The GER is updated as needed, based on evolving plans and agencies priorities. The 2024 GER reflects an expanded vision, with increased participation from emerging space agencies, a stronger emphasis on international cooperation and recognition of the growing role of the private sector.

1.1.2 Benefits Tiger Team

The benefits of space exploration are a core element of the GER's vision. Recognizing the importance of articulating a common perspective on the nature of these benefits, ISECG established the Benefits Tiger Team (BTT) in 2022. The BTT aimed to develop a unified benefits model as a tool to inform and engage stakeholder communities and to guide space policy and decision making. The model also facilitates the alignment of priorities among cooperating space agencies, amplifies the voice of the global exploration community, and provides a common basis on which space agencies may build their own benefits frameworks.

2. Methods

The BTT built on previous collaborative efforts by ISECG agencies to identify the fundamental benefits themes common to all space exploration activities [15]. These previous efforts also highlighted the anticipated benefits to be derived from future human lunar and Martian exploration missions, which were still at the ideation stage at the time.

The BTT sought to expand these fundamental themes into measurable outputs and outcomes resulting from space exploration investments. To develop the unified benefits model, the BTT considered existing ISECG agency reports and frameworks to identify common benefit drivers for space exploration investments across ISECG space agencies and to showcase concrete examples of positive outcomes. While this approach highlighted the variations in reporting practices between agencies, it also demonstrated significant commonalities in outputs and outcomes reported.

The BTT also invited the 27 ISECG participating space agencies to submit benefit examples and success stories stemming from their investments and initiatives in space exploration to capture individual agencies' perspectives on benefits and to identify benefits that are more easily articulated through examples.

3. ISECG's benefits model

The benefits model categorizes 12 benefits into 5 categories (Fig. 2). The benefits are defined as quantifiable, positive changes realised from investments in space exploration initiatives. The benefits represent pragmatic, measurable ways in which space exploration investments deliver positive outcomes for different stakeholder communities.

The exercise highlighted two themes that, while they did not correspond to the definition of benefits, recurred in many of the examples submitted by agencies, reflecting contemporary priorities. These were incorporated as two cross-cutting themes: sustainable exploration and diversification of participants in space exploration; they are reflected across all the benefits.

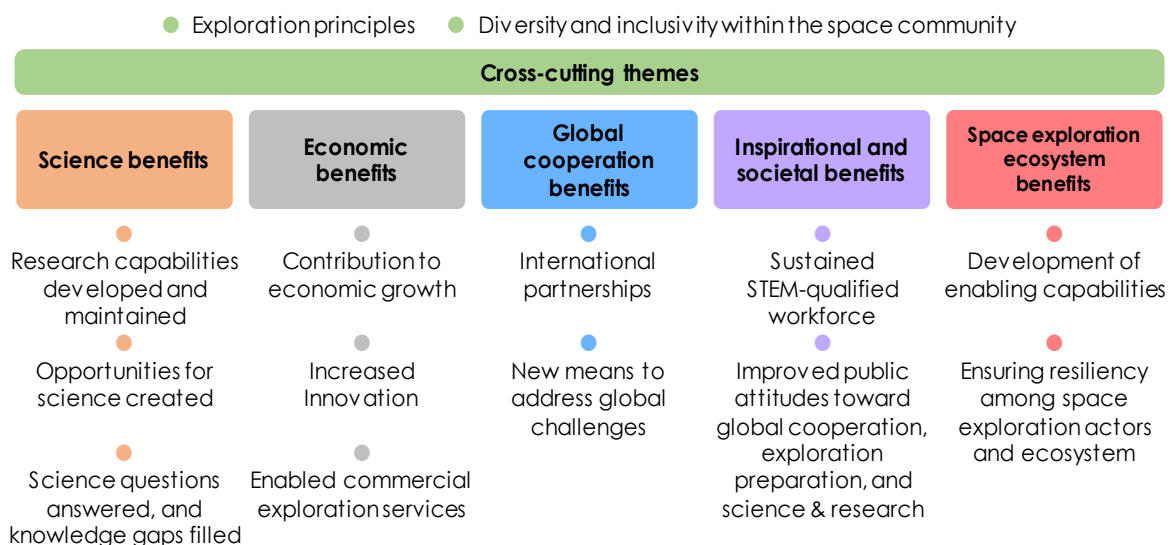


Fig 2. ISECG's benefits model.

This paper introduces the benefits definitions and highlights some of the ways space agencies can enable and assess these benefits. The complete benefits model, including illustrative examples and success stories, is featured in the 2024 ISECG publication *Benefits Stemming from Space Exploration 2nd Edition* [16].

3.1 Science benefits

The essence of exploration is to venture into the unknown to discover what lies beyond the limits of human knowledge. Because of this intrinsic link between science and discovery, one of the benefits arising from space exploration is the creation of new scientific knowledge. Learning more about the universe and the human capacity to live in space accelerates scientific excellence and in turn facilitates the development of new technologies that enable deep space exploration.

Science benefits are realized through the development of unique research platforms and capabilities, the creation of opportunities for researchers and engineers to do research and development and the creation and diffusion of new scientific and technological knowledge.

3.1.1 Research capabilities developed and maintained

The development and operation of research platforms and infrastructure constitutes an early-stage benefit in the chain of space exploration activities.

Deploying science instruments and infrastructure in space allows researchers to carry out investigations in conditions that cannot be found on Earth, including long-duration microgravity, direct exposure to the space environment or data and sample collection from planetary bodies. These unique research capabilities allow scientists to investigate processes in areas such as life sciences, planetary sciences, material sciences and technology development that could not be studied in other ways.

Research capabilities for space exploration can also include environments on Earth that serve as analogues for the challenging conditions in space and on the Moon and Mars. These analogues are instrumental for conducting scientific investigations to better understand the effects of living and working in extreme settings.

3.1.2 Opportunities for science created

Opportunities for science are created by bringing together the resources and conditions that enable researchers and engineers to conduct science.

Institutional and commercial actors can advance space exploration science and technology by providing financial support and access to research facilities,

contributing resources and expertise and securing access to datasets.

Mission science teams, open calls for participation and academic community surveys also create opportunities for scientists from around the world to convene, develop research agendas, establish consortia and shape research priorities. Global science teams create opportunities for smaller or emerging space agencies to engage in international forums and to participate in ambitious space exploration missions.

3.1.3 Science questions answered and knowledge gaps filled

Exploration drives scientific enquiry, while scientific advancements enable further exploration. Robotic missions to the Moon and Mars trigger scientific questions that drive the development of new theories, applications and technologies. The development of new materials, propulsion methods and life support technologies enable long-duration missions to low Earth orbit, the Moon, and Mars.

New scientific and technological knowledge is disseminated through journal articles, conference proceedings, book chapters, and student theses. The resulting technological and scientific advancements in areas such as health, transportation, public safety, energy, the environment, information technology and automation reflect space exploration's tangible impacts on life on Earth.

3.2 Economic benefits

Over the last decade, investments in space exploration from both the public and private sectors have surged. Space exploration supports employment and entrepreneurial capacities, fostering highly skilled workforces, giving rise to start-ups and small technology enterprises and enabling the development of new products and markets. The returns on investments in space exploration programmes may not always be direct or immediate, but these efforts always contribute to economic growth and technology innovation.

Investments in space exploration realize economic benefits through direct economic impacts, increased innovation and the creation of new commercial exploration products and services.

3.2.1 Contribution to economic growth

Space exploration contributes to economic growth through direct job creation, indirect supply chain expenditures, and induced spendings of employees and contractors in the wider economy. These economic impacts translate into increases in gross domestic product (GDP) and tax revenues for governments.

Socioeconomic studies highlight that space exploration investments focus on sectors with robust output and employment multipliers, signifying the sector's potential to drive significant economic growth. Contribution to economic growth is assessed through various economic impact models.

3.2.2 Increased innovation

Space exploration is a driver of technology-based innovation. Many high-value products and services can be linked to technologies that were initially developed for space.

The unique, stringent challenges of space exploration accelerate technological innovation, requiring compact, lightweight and highly reliable systems. Engineers, scientists and technicians must push beyond the existing knowledge base to develop innovative solutions, many of which ultimately lead to new or improved products, processes and services in space and on Earth.

Space agencies facilitate technology transfer and commercialization through dedicated support programs. Innovation outcomes are assessed through case studies and metrics on spin-offs, patents and licenses.

3.2.3 Commercial exploration services enabled

Commercial exploration services provide many advantages by enabling broader participation in space activities, lowering the cost of access to space, reducing cost risks to users and increasing redundancy and competitiveness through multiple service providers.

By encouraging the development of commercial capabilities, space agencies can pave the way for the development of commercial exploration products and services. The growing economy in low Earth orbit continues to expand markets such as on-orbit manufacturing, pharmaceutical research and private astronaut flights. New commercial services in the lunar environment offer opportunities for companies to conduct science, test their technologies and demonstrate and showcase their capabilities.

3.3 Global cooperation benefits

Space exploration missions serve as one of the strongest demonstrations of the power of peaceful cooperation among countries to achieve common goals. The success of these missions requires a high level of coordination, complex and advanced technologies for human and robotic spaceflight, and extensive resources. The collaborative pursuit of these ambitious goals also fosters a shared perspective on the global challenges facing humanity.

Global cooperation benefits are created by fostering the creation of new international partnerships and reinforcing existing ones and by uniting nations to solve global challenges.

3.3.1 International partnerships

Space exploration is a grand project that cannot be realized without international partnerships. In turn, the development and strengthening of international partnerships is a benefit of space exploration, fostering the trust and collaboration among nations and organisations that are essential for diplomacy and effective working relations.

Space exploration requires a variety of technologies, expertise and investments and is built on international partnerships. International missions create opportunities for space agencies and private companies of various sizes to contribute to exploration missions by leveraging their national expertise, pooling resources and promoting an ongoing sense of partnership. Partners share the risks as well as the benefits, thus reducing the impact of program delays on any one country.

3.3.2 New means to address global challenges

Global cooperation in space exploration has also led to significant advances in addressing global challenges.

Established cooperation and technologies for space exploration play an important role in addressing social and environmental challenges on Earth, such as climate change and limited access to food, water and health care. For example, many of the life support systems developed for the resource-constrained conditions of space have applications to improve the lives of people living or working in isolated or harsh environments on Earth.

3.4 Inspiration and societal benefits

Inspiration and societal benefits are at the heart of space exploration. Over the last several decades, space exploration has significantly impacted the way society views and is influenced by science, technology, engineering and mathematics (STEM)-related activities. With greater access to resources, media and information, countries around the world are expanding their capabilities to engage their communities on space initiatives.

The growing interest by society and younger generations in space exploration ultimately helps expand and sustain more robust STEM workforces and improves public attitudes toward global cooperation, future space exploration, science and research.

3.4.1 Sustained STEM-qualified workforce

From early education to young professionals, the global space community has provided greater opportunities for young people to participate in and contribute to space exploration.

Many space agencies maintain educational offices to further engage communities and promote programmes for students and young professionals. Outreach activities, including local events, competitions and educational programmes, help to inspire students to pursue STEM studies and connect with future leaders in space. These hands-on STEM activities provide excellent opportunities to engage, educate and train students to develop the required knowledge base, competencies and skills to address the global exploration challenges of the future.

In addition, some agencies and organisations offer programmes that allow students to engage with real space missions or activities. Through these initiatives, agencies across the globe have seen significant increases in interest and have expanded their programs to accommodate a growing number of participants.

3.4.2 Improved public attitude toward science, research and global cooperation

Space exploration encourages humankind, especially younger generations, to commit to working together and inspires society to attempt incredible feats. Over the last decade, numerous emerging and established agencies have continued to push the boundaries of space exploration, achieving inspiring “firsts” that have not only garnered public support and national pride, but have also encouraged global cooperation toward goals previously thought impossible.

The expansion of capabilities and access to education and opportunities have also promoted greater diversity in the space community. Diversity of thought, background and identity have allowed agencies to connect with broader audiences and encourage greater participation from a variety of different communities. Workforce diversity remains a core value for many space agencies and contributes to employee satisfaction and retention.

Likewise, greater accessibility and representation of space exploration in education and media have significant cultural impacts across society. Social media, online resources and outreach activities make it possible for the public to engage directly with space-related entities. Many space agencies or space-related entities maintain social media accounts that give viewers an inside look at ongoing missions, operations or experiments. Agencies offer opportunities to engage directly with astronauts, scientists and engineers through

online sessions or in person meet and greets. The inclusion and visibility of space exploration in other disciplines, such as art, film and photography, have further inspired society and increased public support.

3.5 Exploration ecosystem benefits

Sustained investments in space exploration maintain a robust space sector that is ready to address the needs of today and tomorrow. Exploration projects are built on a highly specialized workforce and technological capabilities that, once lost, are costly and time-consuming to rebuild. The complexity and long duration of space exploration missions drive cooperation among a wide ecosystem of organisations, including international space agencies and private companies.

Exploration ecosystem benefits are created by maintaining exploration-enabling capabilities and by fostering a diverse network of participants and contributors.

3.5.1 Development of enabling capabilities

Key enabling technologies can be applicable not only to space exploration, but also to other types of space missions and operations. The development of the technologies is just the first step. Cooperation agreements among the partners of a mission must be negotiated to allow emerging space agencies to become part of a worldwide space exploration ecosystem.

3.5.2 Ensuring resiliency of space exploration actors and ecosystem

The growing number and variety of actors involved in the space exploration domain, including large, small and emerging space agencies, spurs new initiatives, multiplies competences and strengthens the overall exploration ecosystem. Emerging space agencies can contribute to larger international exploration missions that they would not be able to field on their own (e.g., providing a key technology).

5. Discussion

Space exploration produces a wide range of benefits — positive, tangible changes — for people around the world. These benefits range from the very immediate, like creating jobs and developing new technologies, to the more general and philosophical, like inspiring young people to pursue educational and professional opportunities in science, technology, engineering, mathematics and the arts. Some of these benefits are easier to directly measure than others, but this does not mean that they are inherently more important.

ISECG’s model aims to capture the breadth of benefits, organising them into benefit categories and cross-cutting themes. Rarely does a single exploration

activity have a direct relationship to an individual benefit; rather, the international space exploration endeavour touches many areas of life, as indicated by the mapping of categories to different examples in ISECG's Benefits Stemming from Space Exploration publication.

Benefits are among the key factors that animate international cooperation in space exploration. Generating benefits for the public is one of the guiding principles captured in ISECG's GER, a shared vision for enduring space exploration and international cooperation; it is therefore one of ISECG's most important areas of focus.

Products like ISECG's Benefits Stemming from Space Exploration publication capture the global nature of space exploration, which is increasingly conducted through international collaboration and in partnership with commercial organisations. While many participating agencies issue their own reports about the scientific, economic and societal benefits of their space exploration efforts, a common benefits model can emphasize that many of these benefits transcend national borders, improving life for all of humanity.

6. Conclusions

While space exploration is an expensive, inherently risky endeavour, the benefits it offers to individual countries and to humanity at large make it a worthwhile one. Earth's nations choose to explore space, increasingly in cooperation with one another, in no small part because of how exploration improves life back on Earth. Benefits are not simply a justification for the cost of spaceflight; they are one of its key outcomes.

Communicating these benefits is crucial for space agencies to build relationships with national decision-makers and citizens. These benefits also transcend nationality, forming the basis for international collaborations and improving the lives of people around the world. ISECG's BTT highlights benefits from across its participating agencies as part of its mission to foster international cooperation in space exploration. As exploration expands and humanity journeys to increasingly distant destinations, the benefits for people back on Earth will also grow.

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