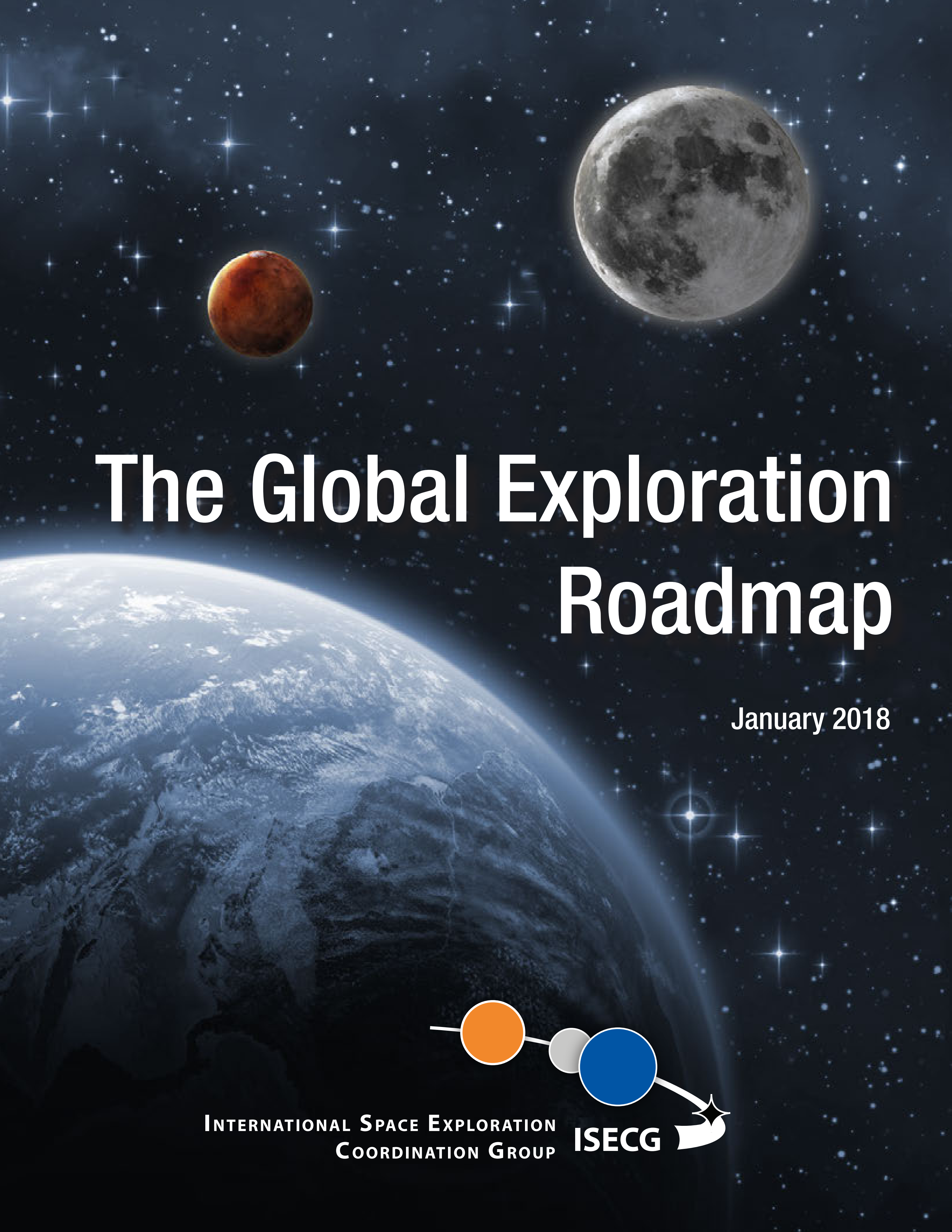

The Global Exploration Roadmap

January 2018

International Space Exploration Coordination Group

ISECG

What is New in The Global Exploration Roadmap?

This new edition of the Global Exploration Roadmap reaffirms the interest of 14 space agencies to expand human presence into the Solar System, with the surface of Mars as a common driving goal. It reflects a coordinated international effort to prepare for space exploration missions beginning with the International Space Station (ISS) and continuing to the lunar vicinity, the lunar surface, then on to Mars. The expanded group of agencies demonstrates the growing interest in space exploration and the importance of cooperation to realise individual and common goals and objectives.

This third edition of the Global Exploration Roadmap reflects consensus about the importance of the Moon on the pathway to Mars and adds refinements in each step along this path as agencies continue to make individual and collective progress. The roadmap demonstrates how capabilities under development or study around the world could enable a sustainable future of human and robotic space exploration. Refinements in this edition include:

- A summary of the benefits stemming from space exploration. Numerous benefits will come from this exciting endeavour. It is important that mission objectives reflect this priority when planning exploration missions.
- The important role of science and knowledge gain. Open interaction with the international science community helped identify specific scientific opportunities created by the presence of humans and their infrastructure as they explore the Solar System. Although summarised here, details of this interaction have been published in a supplemental white paper on *Scientific Opportunities Enabled by Human Exploration Beyond Low-Earth Orbit* which is available at **www.globalspaceexploration.org**.
- The introduction of an international deep space Gateway concept. The deep space Gateway is a small human-tended facility around the Moon which will play an important role in sustainable human space exploration. Initially, it supports human and robotic lunar exploration in a manner which creates opportunities for multiple sectors to advance key goals.
- The recognition of the growing private sector interest in space exploration. Interest from the private sector is already transforming the future of low Earth orbit, creating new opportunities as space agencies look to expand human presence into the Solar System. Growing capability and interest from the private sector indicate a future for collaboration not only among international space agencies, but also with private entities pursuing their own goals and objectives.

ISECG space agencies envision a future of expanding partnerships and collaboration, with an increasing number of actors, as a means to realise the ambitious shared goal of sustainably expanding human and robotic presence into the Solar System.

Australia

Canada

China

European Space Agency

France

India

Italy

Japan

Republic of Korea

Russia

Ukraine

United Arab Emirates

United Kingdom

United States

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Chapter 1:
Why We Explore

"The Earth is the cradle of humanity, but mankind cannot stay in the cradle forever."

~ Konstantin Tsiolkovsky

A Shared Roadmap for Expanding Human Presence into the Solar System

This shared roadmap embraces government and private sector strategies for expanding human presence in low Earth orbit, to the Moon and on to Mars. Government investments in space exploration capabilities and missions serve an important role by advancing technologies, reducing risks and identifying new markets where competition can spur innovation that generates further benefits.

The International Space Station (ISS), continuously crewed since 2000, shows the benefits and potential of human activity in low Earth orbit. The ISS hosts ongoing scientific investigations sponsored by government and non-government entities. Through international collaboration, over 2,100 such activities have been implemented with more ongoing. The ISS is an invaluable long-duration flight analogue for future human deep space missions enabling research to address human health and performance risks as well as serving as a testbed for critical technologies. It is also used for educational and outreach activities, reaching millions of students and the interested public around the world each year. Lastly, the ISS is facilitating the economic development of low Earth orbit, which will remain an important destination for human activity and research in space.

ISECG space agencies envision that by the mid 2020's a Gateway in the lunar vicinity will open the space frontier for human exploration of the Moon, Mars and asteroids as we expand human exploration and commerce into deep space. The Gateway will support activities on and around the Moon while also serving as a technology and operations testbed allowing human explorers to address the challenges and risks of deep space exploration and conduct scientific investigation of our Solar System.

Utilising the Gateway with a partially reusable lunar lander (under study by JAXA, ESA and Roscosmos), human missions to the lunar surface are envisioned. These missions will also advance some of the capabilities and technologies needed for the exploration of Mars. Astronauts can advance the preparatory work of robotic missions in assessing the potential for resources on the lunar surface and techniques for using them to make exploration sustainable.

Ambitious visions like the ones shown below have the power to unite in a common cause and inspire future generations. Human space exploration has fascinated humanity since the start of the space age in the 1950's and inspired a multitude of engaging visions, promoted by individuals, space agencies and private sector entities. The Global Exploration Roadmap is consistent with these visions and represents a common pathway which can enable their realisation.

The Global Exploration Roadmap represents a blueprint of next steps for the current and next generation of explorers. Governments, the private sector and academia will determine investments and partnerships that can translate this blueprint into tangible progress extending human presence, with the associated benefits.

The Moon Village vision entails an incrementally growing ensemble of capabilities for multiple uses and is open to multiple users.

The UAE vision of Mars 2117 will drive technologies for space exploration such as energy, water and food security that will also benefit life on Earth.

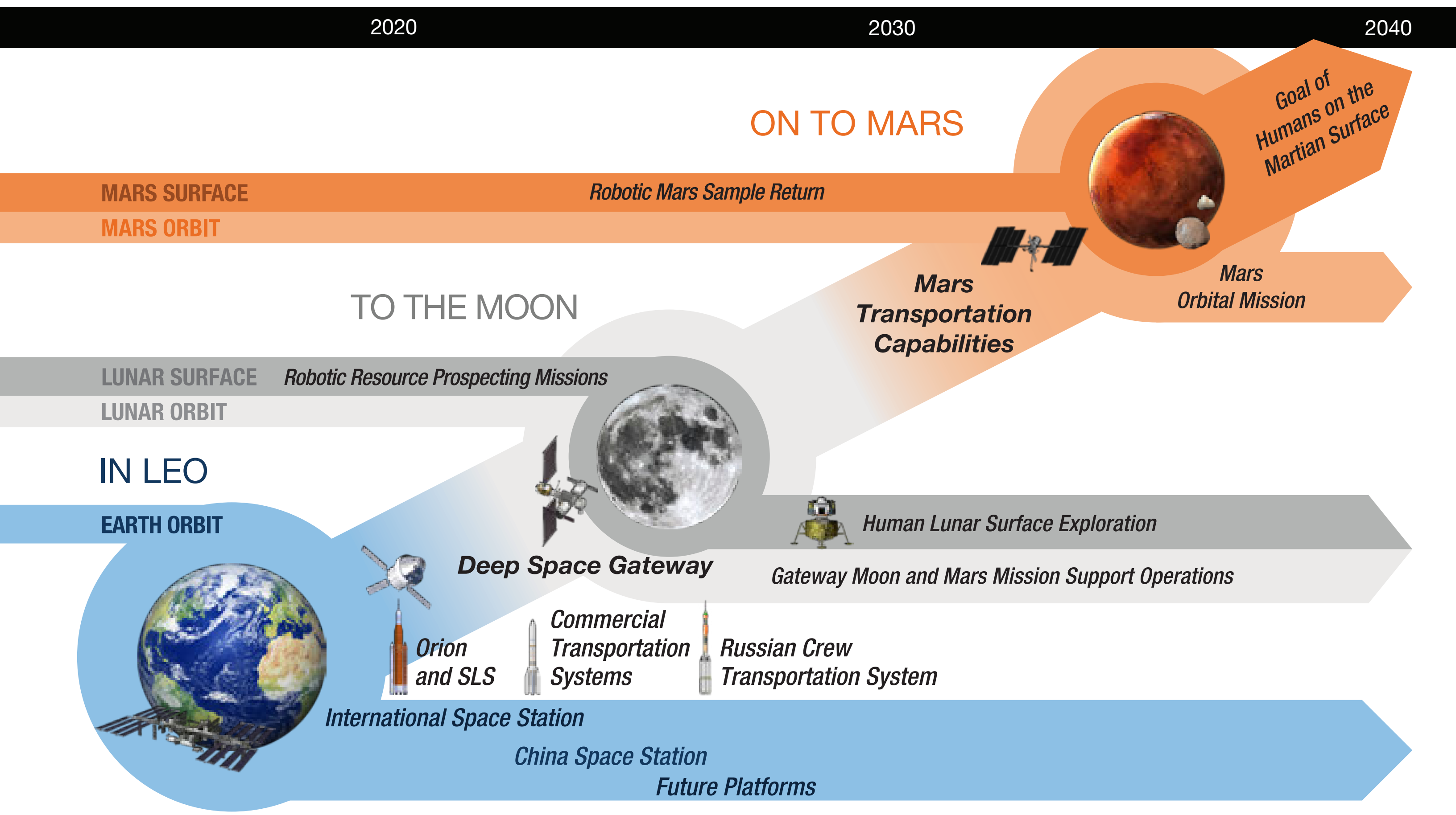
Expanding human presence into the Solar System has the unique capacity to inspire citizens around the world to create a better future.

The knowledge and technologies derived from this endeavour expand our understanding of the Universe, create economic opportunities and help address grand challenges faced here on Earth. A partnership between humans and robots is essential to the success of this venture. Robotic missions accomplish world-class science while also serving as our scouts and proxies, venturing first into hostile environments to gather critical information that makes human exploration safer. Humans will bring their flexibility, adaptability, experience, dexterity, creativity, intuition, and the ability to make real time decisions to the missions.

The Global Exploration Strategy: the Framework for Coordination, released in 2007, presents a vision for globally coordinated human and robotic space exploration focused on Solar System destinations where humans may one day live and work. In this global vision, robotic missions precede human explorers to the Moon, near-Earth asteroids, and Mars in order to unveil many of their secrets, characterise their environments, and identify risks and potential resources. Human exploration then follows in a coordinated manner that is affordable and sustainable, which both benefits and contributes to space agencies around the world achieving their goals and objectives.

The ISECG was established in response to the Global Exploration Strategy. The Global Exploration Roadmap depicted below has been developed to aid in turning this vision into reality. While not committing individual agencies to specific steps and activities, the Global Exploration Roadmap serves as a reference for generating innovative ideas and solutions to address the challenges ahead together.

The Global Exploration Roadmap



The Benefits of Space Exploration: A grand endeavour pursued by nations seeking to gain new knowledge, inspire and drive innovations.

Human and robotic space exploration responds to the deeply rooted quest of humankind for answering questions on the origins and nature of life in our Universe and extending human frontiers. Space exploration brings direct and indirect benefits to society. Benefits can be categorized into these fundamental areas:

Innovation and Economic Growth. Space exploration is a driver for innovation. It has contributed advancements in technologies touching every aspect of everyday life, from health and medicine, public safety, consumer goods, to energy and the environment, industrial productivity and transportation. Space exploration will continue to be an essential driver of technology and innovative ideas, providing opportunities for other sectors to partner with the space sector on joint research and development. For example, water recycling system innovations required to support ISS have resulted in technologies and approaches that are applied on Earth for conservation activities and in disaster relief areas. Enhancements in water recycling and environmental control needed for crew missions into deep space will improve these technologies for terrestrial use, returning these benefits to both the public and private sector. New technologies stemming from space exploration also benefit other in-space applications for terrestrial use such as satellites used for meteorology or communications.

In the last several years, job creation and economic growth have been accelerated by private investments in the space sector. Private investments and competition are stimulating the economic development of low Earth orbit, generating innovations that promise to make space exploration more affordable and sustainable.

Knowledge Gain. The benefits from space exploration are rooted in the generation of new knowledge, which is of intrinsic value to humankind. Scientific knowledge acquired from space expands humankind's understanding and frequently unlocks creative and useful Earth-based applications for society. For example, studies of the human body's response to extended periods in the microgravity environment of the ISS are improving our understanding of the aging process. Fundamental scientific studies of the Martian environment, its evolution and current state represent important benchmarks of terrestrial planetary evolution, and hence, provide a model that scientists believe will aid our growing

Image Credit: Project neuroArm, University of Calgary

Advanced Medical Robotics: Canadian medical robotics technology born of Canada's space robotics designed by MacDonald, Dettwiler and Associates, Ltd. (MDA) for the U.S. Space Shuttle and the ISS, neuroARM (above) is the world's first robot capable of performing surgery inside magnetic resonance imaging (MRI) machines, and helps neurosurgeons perform precise surgical techniques with real-time imagery. A Guided Autonomous Robot was also developed using this technology and is in clinical trials. It works inside an MRI machine and helps surgeons locate and identify breast tumours and perform highly dexterous, precise movements during biopsies.

Image Credit: NASA

Remote Medical Care: Provision of medical care to astronauts in space has similar challenges to that provided to patients in disaster or remote areas on Earth like northern communities in Canada. Vast distances and the lack of local access to medical specialist expertise and analytical and imaging capabilities make it a challenge to diagnose and treat an injury or illness. Exploration missions will have the additional burden of not being able to evacuate sick crewmembers back to Earth. Already today, medical care has become more accessible in remote regions by use of small ultrasound units, telemedicine and remote guidance techniques pioneered for use on the ISS.

Image Credit: NASA

Water Purification: Whether in the confines of the ISS or a tiny village in sub-Saharan Africa, drinkable water is vital for human survival. Unfortunately, many people around the world lack access to clean water. Using technology developed for the ISS, at-risk areas can gain access to advanced water filtration and purification systems, making a life-saving difference in these communities. The commercialisation of this station-related technology has provided aid and disaster relief for communities worldwide.

understanding of climate change processes on Earth. In the longer term, the knowledge accumulated over many missions and the expansion of human presence into the Solar System will help people gain perspective on the fragility and rarity of our ecosphere in the Universe and on humankind's accomplishments, potential, and destiny.

Global Cooperation: Partnership to Address Global Challenges. Sustainable space exploration is an inherently worldwide endeavour. The challenges associated with extending human presence in a sustainable manner into space are driving the creation of new partnerships at all levels of society, including governmental, industrial and academic organizations around the world. The ISS is an exceptional example of how partners from different cultures can work effectively together to advance common goals. Collaborative research on the ISS in many disciplines has significantly multiplied the global reach of results and knowledge.

Such global cooperation builds on each other's interests, strengths and capabilities, taking advantage of the opportunity to share views and leverage both complementarity and diversity. Cooperation among different stakeholders has generated synergies along the entire value chain, including exchanging know-how on space project best practices, and spin-offs of innovative technologies. Newly forged global partnerships may offer resources for addressing the global challenges facing humankind today and in the future.

Culture and Inspiration. Space exploration offers a unique and evolving perspective on humanity's place in the Universe. It stimulates curiosity and the ability to see the bigger picture. By uncovering new information about the beginnings of our Solar System, space exploration brings us closer to answering profound questions that have been asked for millennia: What is the physical nature of the Universe? Is the destiny of humankind bound to Earth? Are we and our planet unique? Is there life elsewhere in the Universe? The excitement and enthusiasm generated by space exploration attracts young people to careers in science, technology, engineering and mathematics, and increases public interest and support of science and exploration. Motivating our youth to study and achieve is a common desire shared by all nations.

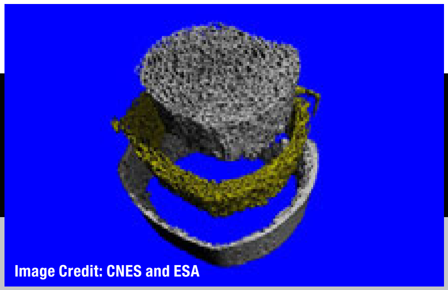


Image Credit: CNES and ESA

Measure of Bone Architecture and Bone Quality: During spaceflights, astronauts present a fast bone loss, about ten times faster than the fastest similar processes on Earth. Space research has contributed to better understand the effects of mechanical constraints on bone loss. The ERISTO project, co-founded by CNES and ESA, has enabled the development of innovative tools to measure bone architecture and bone quality that are currently used pre- and post-flights as well as for the routine practice of clinical medicine.

Earth Observation: Images from orbit can help with rapid response efforts to floods, fires, volcanic eruptions, deforestation, harmful algal blooms and other types of natural events. The ISS passes over more than 90 percent of the Earth's populated areas every 24 hours. An imaging system aboard the station, ISS SERVIR Environmental Research and Visualization System, captured this photo of Mt. Etna, Italy.

For more information on space exploration benefits:

CNES: https://cnes.fr/en/page-intermediaire/CNESMAG
CSA: http://www.asc-csa.gc.ca/eng/about/everyday-benefits-of-space-exploration/
ESA: http://youbenefit.spaceflight.esa.int/
ISECG: http://www.globalspaceexploration.org
JAXA: http://iss.jaxa.jp/kiboresults/benefits/
NASA: https://spinoff.nasa.gov/Spinoff2017/index.html
Roscosmos: https://www.roscosmos.ru/

Goals and Objectives

Recognising the importance of delivering benefits to stakeholders, space agencies have identified five common space exploration goals and associated objectives. These goals and objectives reflect the integrated nature of science and exploration and also build on the synergies that exist between human and robotic space exploration missions. The formulation of goals and objectives is an iterative process that reflects ongoing refinements as agency priorities evolve.

Expand Human Presence into the Solar System

- Ensure continuity for human spaceflight and continued utilisation of low Earth orbit
- Enable sustained living and working around and on the Moon
- Enable sustainable human missions living and working around and on Mars

Understand Our Place in the Universe

- Study the origin and evolution of the Earth and the Moon system, the Solar System and the Universe
- Search for evidence of past or present life and the origin of life on Earth
- Investigate habitability of potential human destinations

Image Credit: UAE

Culture and Inspiration: Space is inspiring young men and women to pursue careers in science, engineering and technology. In the space sector of the United Arab Emirates, over 40% of the workforce are female. Since 2000, the UAE has carried out an extensive range of space activities with ambitions set significantly higher for the future. The development and use of space technology will contribute to the diversification of the national economy.

Image Credit: NASA

Temperature-Regulating Fabrics Keep Babies Comfortable: Like ice cubes in a drink, phase change materials absorb heat as they change from solid to liquid, and, if exposed to colder temperatures, they release that heat as they refreeze. Phase change material advancements driven by spacesuit needs led to the creation of fabrics incorporating phase change materials, most recently commercialised by San Francisco-based Embrace Innovations in wraps and blankets that help keep babies at an optimal temperature.

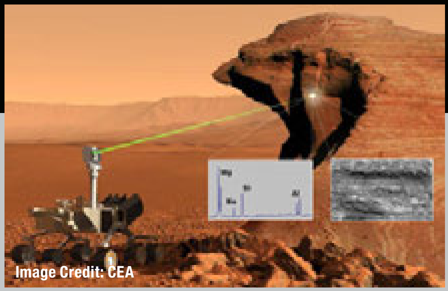


Image Credit: CEA

Mars Science: The French ChemCam instrument on the Mars Science Laboratory, Curiosity, fires a laser and analyses the elemental composition of vaporised materials on the surface of Mars. Mars has the greatest similarity to Earth in past and current planetary processes, and may have the best record of when life started in our Solar System and of catastrophic change in planetary evolution. As we learn more about Mars (surface, interior, atmosphere, hydrosphere and potential for supporting biology) our understanding of the Earth and potential risks to this amazing planet will be dramatically improved.

Engage the Public

- Inspire and educate
- Create opportunities for participation in space exploration
- Deliver benefits to society

Stimulate Economic Prosperity

- Promote industrial capability and competitiveness for space exploration
- Facilitate the development of commercial markets at exploration destinations
- Promote collaboration with the private sector

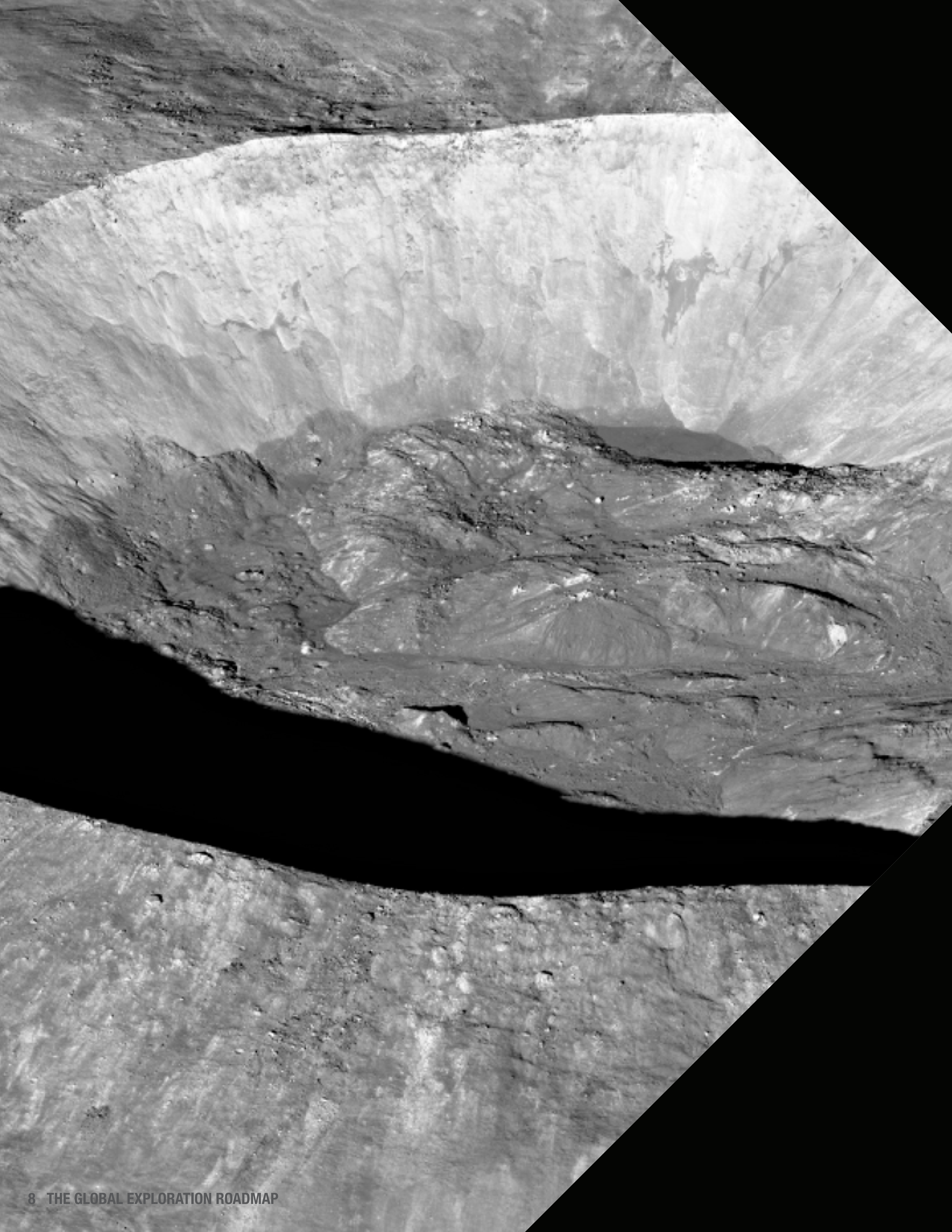
Foster International Cooperation

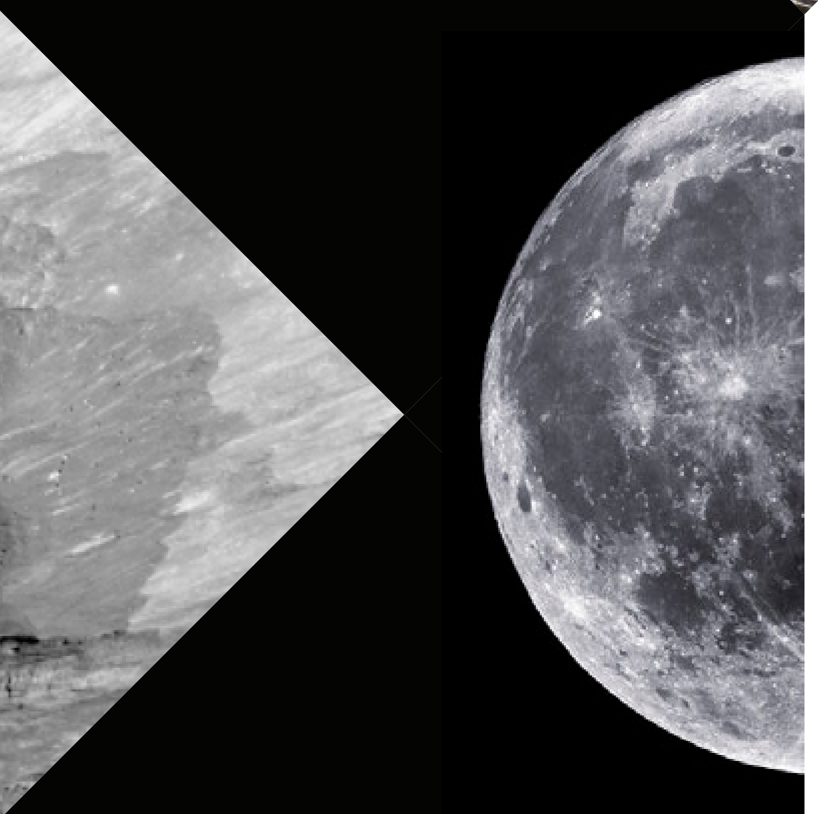
- Encourage and embrace the participation of nations in space exploration initiatives
- Promote interoperability to increase opportunities for international partnerships

Image Credit: ACCESS

New Materials for Better Planes: The investigation of new metallic alloys such as titanium aluminide onboard the ISS as well as relevant techniques for their utilisation has contributed to the development of new turbine blades for the Airbus A320neo. These titanium aluminide blades are significantly lighter than the usual blades, while showing great strength and little corrosion. With the new material, jet engines are quieter, more fuel efficient and eco-friendly.

Plant Research: Innovation in meeting human needs by more efficient use of mineral, water, energy and food resources. The Commonwealth Scientific and Industrial Research Organisation (CSIRO) has an extensive program in plant research and works closely with industry. CSIRO is the federal government agency for scientific research in Australia. In September 2017 the Australian Government announced the formation of the Australian Space Agency heralding a new future for Australian space development.





Chapter 2:
The Mission Scenario

"The journey of a thousand miles begins with one step."

~ *Chinese Proverb*

In Low Earth Orbit, to the Moon, on to Mars

Several ISECG space agencies are developing human space exploration capabilities required to venture out beyond low Earth orbit in partnership. For NASA, these initial enabling capabilities consist of a heavy lift launch vehicle (the Space Launch System/SLS), an exploration crew vehicle (Orion), and updated ground launch systems. NASA's Space Launch System provides a critical heavy-lift capability powering people and cargo to the Moon and beyond. It also opens new possibilities for other payloads, including robotic scientific missions to places like Mars, Jupiter and beyond. Offering the highest-ever payload mass and volume capability and energy to dramatically reduce travel times to deep space destinations, SLS is designed to be flexible and evolvable in order to meet a variety of crew and cargo mission needs.

The Orion Spacecraft is built to take four crewmembers farther into space than ever before. Orion will serve as the exploration vehicle that carries crew beyond the Earth and provides safe reentry at the high-return velocities typically needed for deep space missions. The Orion service module is built in Europe and provides in-space propulsion capability, attitude control, power, water and oxygen needed for a habitable environment.

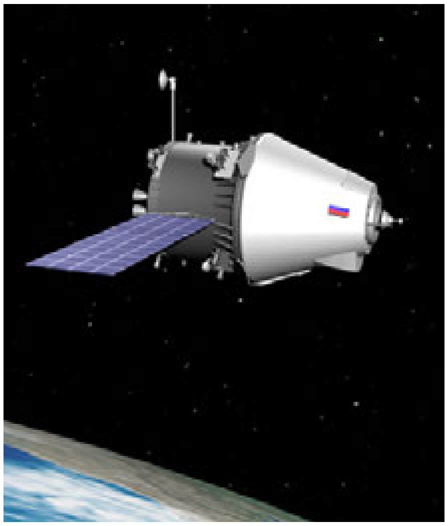
Russia will begin testing a new crew transportation system in the early 2020's. Initial flights to the ISS will demonstrate the new system that will eventually be used for missions to the Moon. By the end of the 2020's, the Russian super-heavy launch vehicle with the crew transportation system will be ready for human flights to the Moon. Prior to this, several robotic precursor missions will explore the Moon's surface and test technologies as a part of the Russian lunar program.

Sustainability Principles

The following set of principles guide development of the Global Exploration Roadmap. They represent attributes of a sustainable human space exploration endeavour.

- **Affordability – Innovative approaches to enable more with available budgets**
  Cost must be a consideration when formulating exploration programmes as well as throughout programme execution. Architectures should favour reusable and reliable in-space systems implemented in partnership to share cost.
- **Exploration Benefit – Meet exploration objectives and generate public benefits**
  Sustainable human space exploration must respond to exploration goals and objectives and provide value to the public and other stakeholder communities. Synergies between space and other domains are crucial.
- **Partnerships – Provide early and sustained opportunities for diverse partners**
  International cooperation is critical for enabling and sustaining increasingly complex exploration missions. Collaborations should consider the long-term interests of each partner, large or small. Collaborations with the private sector, where goals align, can enable new approaches and create markets for services to support space exploration.
- **Capability Evolution and Interoperability – The step-wise evolution of capabilities with standard interfaces**
  Building upon existing capabilities and increasing performance with each step. Using common interfaces and modular architectures facilitates addition of new partners, reduces mass and increases safety.
- **Human-Robotic Partnership – Maximise synergies between human and robotic missions**
  Combining the unique and complementary capabilities of humans and robotic systems enables a greater set of goals to be met effectively, cost-efficiently and safely.
- **Robustness – Provide resilience to technical and programmatic challenges**
  Plans and actions must have flexibility to cope with unplanned changes or crisis situations, whether due to catastrophic events, changes in partner priorities, adjustments in available funding or the evolution of objectives. Dissimilar redundancies of critical functions should be applied early, where practicable.

Orion Spacecraft, NASA, with service module provided by ESA.

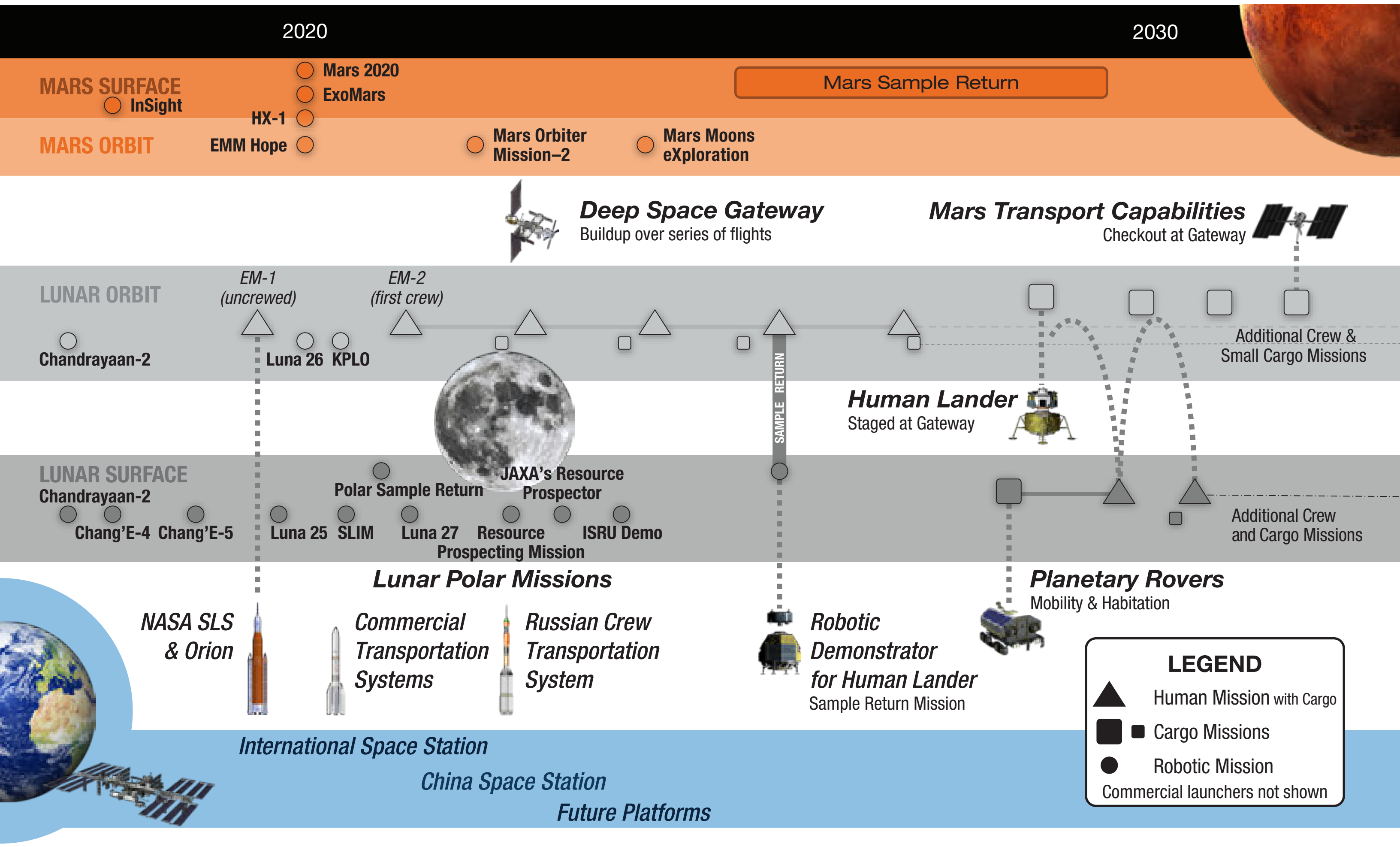


Russian Crew Transport System, Roscosmos.

The Mission Scenario

The ISECG Mission Scenario reflects planned human and robotic missions, as well as conceptual missions under study. While not all agencies will participate in all missions, this mission scenario shows an international collaborative effort and consensus on steps to achieving the common horizon goal of human missions to explore the surface of Mars. It recognizes the shared importance of low Earth orbit and lunar exploration to the sustainability of the endeavour.

ISECG Mission Scenario



The key steps for expanding human presence shown in the ISECG Mission Scenario:

- Low Earth Orbit: Validate needed deep space technologies and capabilities, provide continuity for research in low Earth orbit
- Robotic Missions
  - Demonstrate technologies for human missions
  - Perform surveys or sample returns for science as well as resource and environment assessment
- Lunar Vicinity: Establish a platform (deep space Gateway)
  - Learn more about living in deep space
  - Operate robotic missions to and on the lunar surface
  - Stage crewed missions on the lunar surface (Human Lunar Lander)
  - Enhance science of the Moon and the Solar System
  - Assemble and check-out of the transport vehicle to Mars
- Lunar Surface Missions: Establish a lunar surface capability
  - Support lunar science
  - Prepare and test mission operations for subsequent human exploration of Mars and/or long-duration human activities on the Moon
  - Understand the potential economic implications of lunar development and/or commerce
- Humans to Mars: Enable sustainable human missions to Mars
  - Missions to Mars orbit and surface

Low Earth Orbit: Human activity is here to stay.

THE INTERNATIONAL SPACE STATION

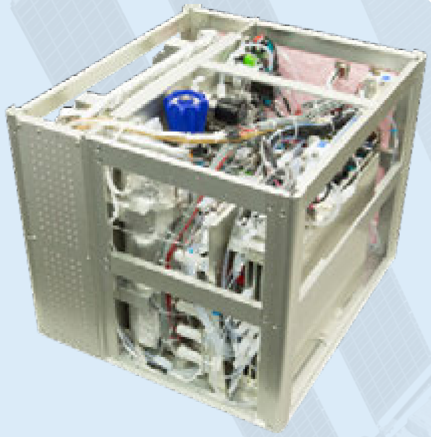
The ISS provides a variety of equipment and systems to support advanced research and development activities. There is equipment to support life sciences, physical sciences and materials science research. Examples are on-board capabilities for rodent research, protein crystal growth, DNA sequencing, cubesat and small spacecraft deployment and additive manufacturing equipment. A steady stream of logistics flights brings equipment to the ISS and returns investigation samples to support timely opportunities for research and analysis. Information on available resources and equipment can be found at **www.nasa.gov/stationfacilities** and on individual ISS partner agency websites.

New research modules on the Russian segment of the ISS will expand the opportunities for research and technology demonstration. New commercial capabilities, including European and US capabilities, are also being added. New US crew and cargo transportation systems are anticipated in the future, providing increased access and beneficial conditions for users. These new crew transportation systems will join the Russian Soyuz which has been essential to ISS operations. These are examples of the benefits of international partnership.

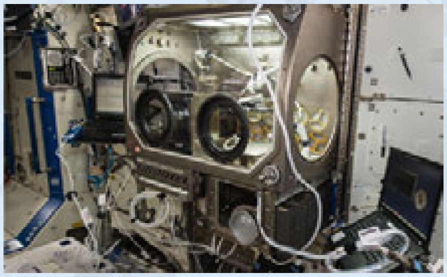
The ISS is a useful platform for performing Earth science, heliophysics, and astrophysics. The ISS is also an essential platform to prepare for human space exploration and much work remains to be done. Human research and exploration technology demonstrations are a significant focus of activity onboard the ISS. Maturing life support systems from the ISS state of the art to the performance and reliability requirements of exploration missions is a high priority for several space agencies.

The ISS serves as an innovation platform where governmental and non-governmental entities alike are exploring opportunities in low Earth orbit. Entrepreneurs, innovators, pharmaceutical companies and other consumer product researchers are all attracted to low Earth orbit for its potential to lead to new products, markets and services. Over 600 payloads have been delivered to the ISS for such purposes. These developments appear to indicate that private sector demand, in addition to space agency demand for humans and their infrastructure in low Earth orbit, will continue far into the future.

International Space Station partner agencies are committed to operation of ISS until at least 2024 and potentially beyond.



JAXA's water recovery system technology demonstration will be delivered to the ISS in 2018.



NASA demonstrates 3-D printing on the ISS.

THE CHINESE SPACE STATION

In September 2010, the Chinese government approved the implementation of their space station project. China's Space Station project is organised in two phases: the first phase includes the Space Laboratory; the second phase includes construction of a Space Station. The Tiangong 2 Space Laboratory was launched in September 2016. Then, the Shenzhou-11 crewed spacecraft and cargo spacecraft docked with it. The China Space Station consists of a core module and two specialised modules. The China Space Station will have an orbital inclination of 42 degrees and an altitude of approximately 340-450 km. The station has a design life of 10 years with the ability to extend service life through maintenance. After the construction is completed, two or three astronauts will live and work continuously for long durations, with the station supporting a maximum of six people during periods of crew rotation. The station is equipped with an external robotic arm and other equipment to support station construction, maintenance and operations.

The Space Station phase is divided into three sub-phases. In the key technical verification phase, the test core module is launched and multiple pilot and cargo spacecraft launches test the core module to validate astronaut long-term presence, regenerative life support systems, flexible solar wing and drive mechanism, control of a large flexible structure, and space station assembly. Following this key technical verification phase, the two specialised modules are launched completing the construction phase. During this period, a number of Shenzhou crewed and cargo spacecraft will be launched to support the completion of construction tasks and carry out scientific and technological experiments simultaneously.

When the Space Station construction tasks are completed, the operations phase begins. The astronaut crew will conduct long-duration missions to conduct scientific and technological research and exploration activities. On the basis of the existing three-module configuration, an additional docking interface is available with the capability of docking an additional permanent element. The Space Station can accommodate other countries' spacecraft access that meets the standards of China's space station and can also be equipped with an external experimental platform and experimental equipment. Additional modules may be added to the Space Station in the future.

The main scientific research and application directions of the Space Station are: space medicine, space life science and biotechnology, microgravity fluid physics, space material science, microgravity basic physics, space astronomy and astrophysics, space environment and space physics, aerospace components, space geosciences and applications, space-based information technology, new aerospace technologies and new applications in space applications.

International cooperation can be based on module level cooperation, on other countries' spacecraft visits, on astronaut joint flights, and on cooperation in space science and space applications research.

FUTURE PLATFORMS

Several private sector companies have announced concepts for commercial platforms, which could be human-tended, to offer services to a diverse set of non-government and government users. In addition to government users, demand is expected to come from private companies conducting research or in-space manufacturing, tourism, and other commercial initiatives that benefit from access to low Earth orbit. The availability of a private sector platform or platforms in low Earth orbit where government sponsored research can be accomplished will be a consideration related to ISS lifetime decisions. Ensuring the continuity of human spaceflight is another major consideration as it is critical to maintain the industry capabilities, technologies and inspirational and aspirational momentum for future generations.

Some agencies are studying future platform designs in order to understand future possibilities, either to be realised through government investment or in partnership with private sector entities. For example, a post-ISS Russian orbital station concept, aimed to continue the success of the ISS and to provide transition to low Earth orbit utilisation with a wide range of benefits for humanity, as well as to create additional opportunities for partnership, is being studied. The goals of these studies are to understand the major characteristics of a user-driven platform, and assess possible government roles in promoting their availability.

ISECG space agencies are increasingly vocal about their need for continued access to low Earth orbit beyond the ISS lifetime. Several have announced commitments to continue research and astronaut development activities with the hopes that these will provide encouragement to private sector entities studying future platforms. ISECG space agencies acknowledge significant developments in the private sector and welcome the emerging space economy around humans and their infrastructure in low Earth orbit as several agencies expand their focus with goals and resources toward human exploration of the lunar environment, Mars and other destinations.

The Lunar Vicinity: The next step for advancing and sustaining human space exploration goals.

Both the orbit and the surface of the Moon play important roles in sustainable human space exploration. A small human-tended facility placed in the lunar vicinity enables human and robotic lunar exploration in a manner that creates opportunities for multiple users to advance key goals and foster a burgeoning presence of humans in deep space.

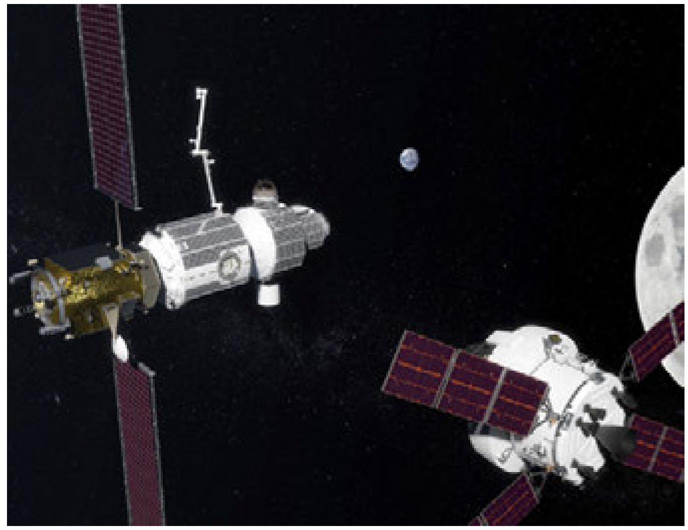
In particular, a human-tended facility in the lunar vicinity enables:

- **Reusability:** The lunar vicinity is an excellent location for staging and refurbishment of reusable elements for exploration of the Moon and Mars. The location contains stable orbits which are outside of Earth's deep gravity environment and provides a convenient jumping off point for reusable robotic and human lunar landing systems including refuelling and servicing between missions.
- **Testing:** Deep space electric propulsion systems can be tested. Also, the environment of the lunar vicinity is equivalent to what astronauts and spacecraft will experience in deep space. Technologies, procedures and risk management protocols can be tested in relative proximity to Earth in case of an emergency. Prior to departing for 2-3 year missions to Mars, in-space capabilities can be tested to assure flight readiness.
- **Accessibility:** The lunar vicinity is reachable by government and commercial launch transportation systems promoting robustness and opportunity. There are many possibilities for commercial services and collaborations between government and the private sector.

Lunar Vicinity Orbits Support a Variety of Exploration Objectives

Balancing orbital energy between the Earth and the Moon gravity wells, and maintaining favourable communications and thermal attributes, are important considerations for lunar orbit locations. The most promising locations consist of a family of halo orbits around the collinear Earth-Moon Libration points that pass within a few thousand kilometers of the lunar surface every seven days. From this home-base orbit, the Gateway will be relocated within the lunar vicinity, reaching other orbits in support of exploration and objectives while testing advanced propulsion technologies needed for space exploration.

An international deep space Gateway to the Moon and Mars



A concept for the deep space Gateway.

A conceptual international deep space Gateway is the next piece of the architecture that enables a sustainable and affordable future for human space exploration. The first element of the deep space Gateway will be a module that uses a high-power solar electric propulsion system and provides power, command and data services to the rest of the platform. The Gateway will include habitation capabilities to support a crew, a science airlock, a robotic arm and capability for spacewalks. The Gateway will provide communication to Earth and the surface of the Moon, opening up new opportunities for robotic exploration of the scientifically interesting lunar far side and polar regions.

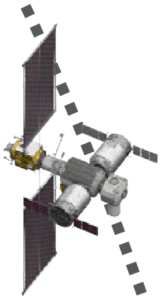
Gateway assembly and operation will be supported by Orion and the Space Launch System, as well as other space transport systems. Initially, it will be visited by a crew of four for missions of a minimum of 30 days at a time. Initial 30 day missions may increase in frequency and length of time as the Gateway evolves and additional transportation systems become available.

The conceptual Gateway includes interfaces for installation of future advanced closed loop life support systems, allowing for testing of new systems and longer crew stays at the Gateway. Gateway crews will perform science, assess habitation capabilities for future missions, and investigate exploration technologies requiring the deep space environment for testing. Private entities may also utilise the Gateway through public private partnerships. When uncrewed, the Gateway will continue to support science and other activities operated from Earth.

Lunar exploration studies by JAXA, ESA, CSA and Roscosmos make use of the Gateway for support to reusable human lunar landers and robotic exploration of the Moon. The Gateway and its crew can provide services and support for future transportation systems heading to Mars.

Science enabled at an international deep space Gateway

The lunar vicinity is a vantage point from which to conduct scientific observations of the Moon, the Earth, and the Solar System, using instruments externally mounted on the Gateway. A Gateway can be used to receive scientifically valuable samples from the lunar surface as well as other Solar System destinations. The Gateway can act as a communication relay for smallsats, cubesats and lunar surface assets. The Gateway enables human physiology experiments in a deep space environment. The lunar surface could be explored remotely using tele-robotics, including deployment of complex surface scientific instrumentation.



Contributions to Mars Mission Readiness

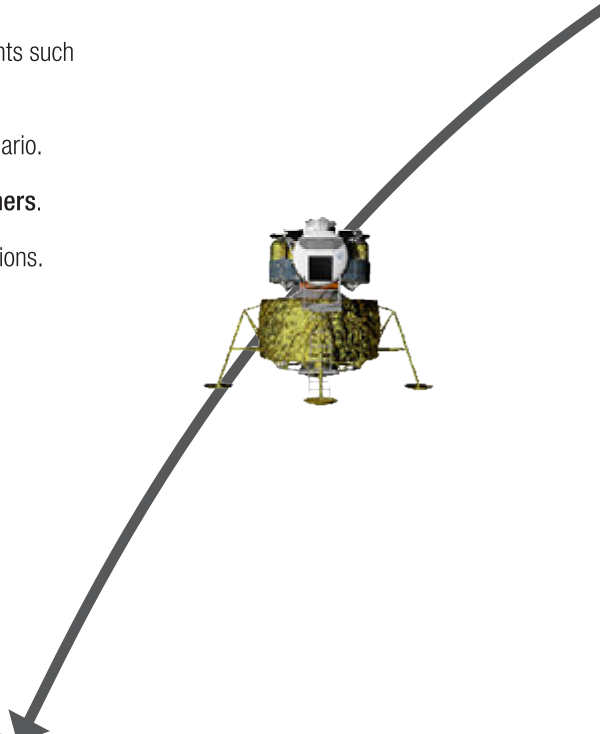
- Transport spacecraft assembly and checkout
- Demonstration of deep space transportation and habitation capabilities
- Autonomous crew operations protocols
- Demonstration of operations with reduced supply chain
- Radiation protection strategies
- Perfection of tele-robotics techniques
- Demonstration of vehicle servicing and refuelling

The Lunar Surface: A series of missions to the lunar surface with 4 crew to explore a cornerstone for Solar System discovery and prepare for Mars.

While conducting scientific study of the Moon with capabilities that can evolve for Mars exploration, space agency investments will advance technologies and buy down the risks which will enable sustained lunar surface operations led by governments or the private sector.

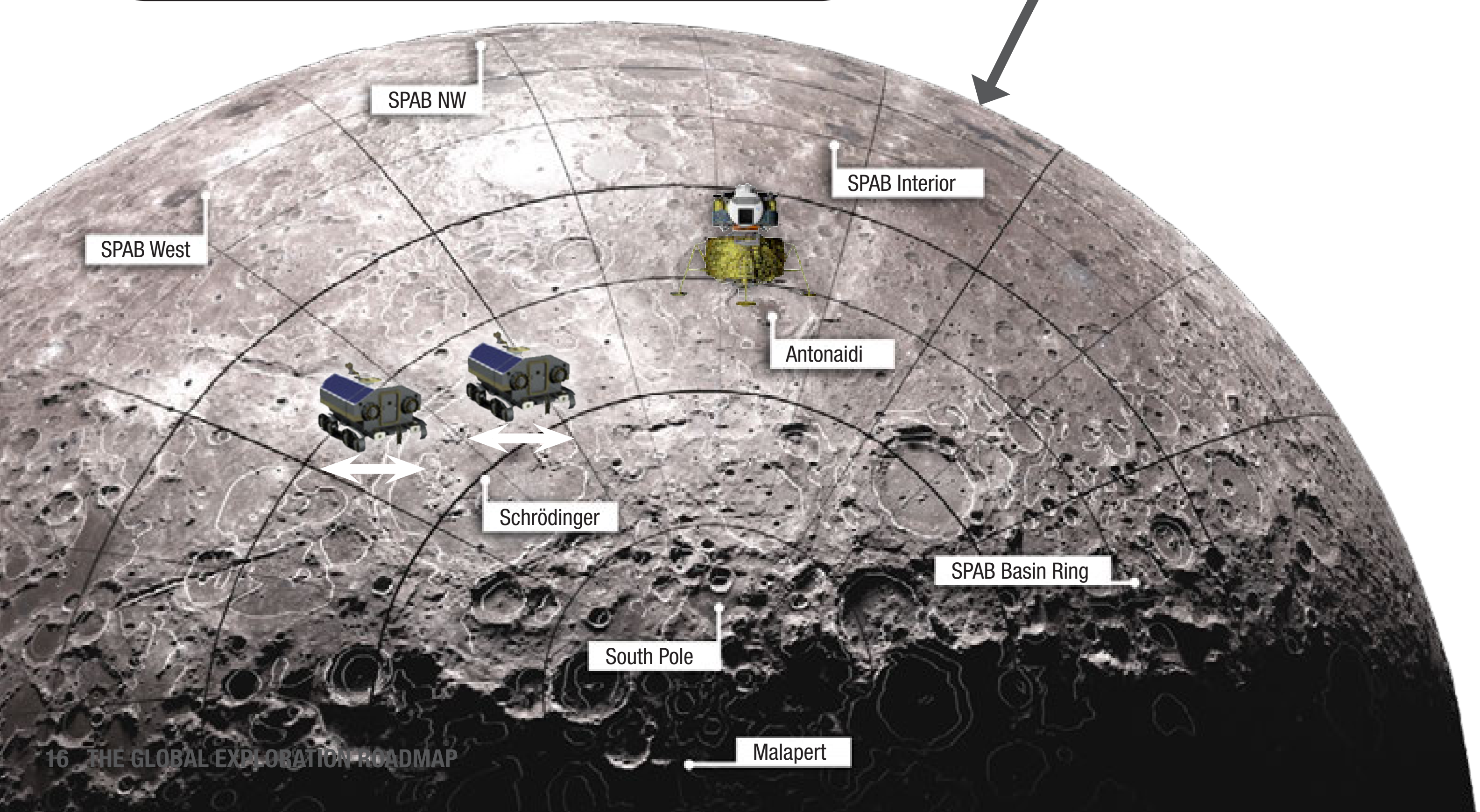
From the Gateway, lunar surface missions can feature:

- **Reusable lunar landers:** shifting cost from developing recurring units to enabling other elements such as an in-space refuelling infrastructure.
- Decreased risk by making the Gateway available as a **crew safe haven** in a surface abort scenario.
- A crew of four to maximise exploration return and provide **flight opportunities for many partners**.
- Advancing and augmenting **in-situ resource utilisation** activities started by lunar robotic missions.

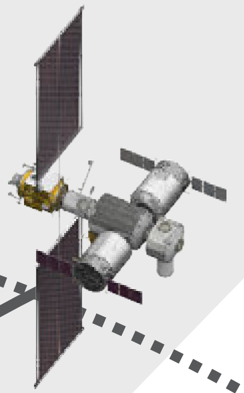


Potential Landing Sites:

The Moon is scientifically diverse with many places to explore. Interesting locations include the lunar poles (both north and south), volcanic deposits, impact craters and basins, and lava tubes or pits. The ability for pressurised rovers to move large distances on the surface between crewed missions would enable regional scientific exploration.

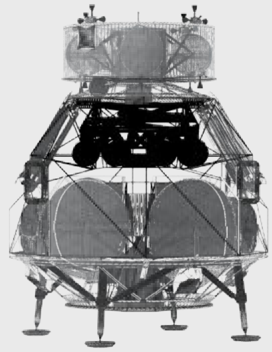


An international architecture for Human Lunar Exploration



Staged at the deep space Gateway, the ***partially reusable lunar lander*** would deliver a crew of four to locations on the lunar surface which will be chosen for high scientific and exploration value. When the crew lands on the surface, ***two relocatable rovers*** (first generation designs of the future Mars rovers) and supplies to enable an extended stay will be waiting for them. Exploring by day, analysing and planning by night, the crew will gather scientific samples and demonstrate in-situ resource utilisation techniques for the ***extended 42 day*** mission (two Moon days, one Moon night). The rovers are moved to meet the next crew, performing science along the way.

Robotic Demonstrator for Human Landing Mission



- Demonstrating critical components of crewed lander and rover
- Building confidence for operations on the surface and in transit to the Gateway
- Delivering of samples from unexplored lunar regions to the Gateway

Human Lunar Elements

4 Crew Reusable Ascent Module

3.7 t Dry
6.2 t Bi-prop
9.9 t Total

Descent Module & Cargo Lander

5.4 t Dry
19.7 t LOX/CH_4
25.1 t Total
10 t Cargo

2 Crew Pressurized Rover (x2)

5 t each

Lunar Science

The Moon preserves many of the geologic processes that occurred early in our Solar System and during the period when life formed. It preserves a record of the impact history over geologic time. Such records have been obliterated on planetary bodies that are active and have atmospheres. The Moon also preserves a record of the Sun's activity in its regolith and the early evolution of terrestrial planets. Volatile deposits at the lunar poles may contain a record of the volatiles transported to the inner Solar System. The radio-quiet lunar far side enables astrophysical investigations into the earliest stages of our universe through the deployment of radio telescopes. Human presence on the Moon would permit detailed geologic mapping, the collection of critical samples for analysis in Earth-based laboratories, and the emplacement of delicate instrumentation, including seismometers and other geophysical instrumentation.

Contributions to Mars Mission Readiness

- **Lander:** Liquid Oxygen/Methane engine demonstration, safe ascent from surface and rendezvous with return spacecraft
- **Rovers:** Long-distance and long-duration mobility, habitation capabilities in dusty environment
- **General:** Demonstration of safe sample return to Earth, in-situ resource utilisation techniques
- **Power:** Advanced nuclear power systems

Mars: Captivating people all over the world, human exploration of Mars would enable detailed in-situ scientific study of the planet and drive technologies for Earth and space exploration.

To achieve this ambition, the necessary capabilities should be developed in an order that logically fits the evolution of missions of increasing duration, complexity and distance from Earth. At minimum, six elements are required to send humans to the Mars surface and back:

1. A deep space transportation vehicle, leveraging work on ISS and investments in the deep space Gateway
2. An entry-descent lander, leveraging investments made for robotic landers and the human lunar lander
3. A Mars ascent vehicle capability, leveraging investments made for the lunar ascent vehicle and Mars sample return
4. Surface habitat and utilities, leveraging investments made for lunar vicinity and surface habitation and power generation
5. Mars surface mobility (EVA and rovers), leveraging investments made for lunar vicinity and surface EVA and rovers
6. Sufficient reconnaissance (orbital and ground) necessary to support human base selection and to inform engineering development of all Mars mission elements

Science opportunities at Mars

Mars has the greatest similarity to Earth in past and current planetary processes, and may have the best record of when life started in our Solar System and of catastrophic change in planetary evolution. Robotic missions have shown that Mars has significant amounts of buried water which is promising for the possible existence of life (past and/or present) and the support of future human explorers. Exploration of Mars will result in answers to profound scientific and philosophical questions such as: How did life start in our Solar System? Did life exist on Mars and does it exist today? What can we learn about Earth's past and future by studying Mars? Building on over 50 years of robotic-enabled science, and eventually sample return, human explorers on the surface of Mars will be critical to revealing the subtleties needed to answer these complex and fundamental questions. Humans will make possible intelligent sampling in geologic context, iterative environmental field investigations and sample preparation/analyses. Humans will advance a multi-disciplinary set of scientific objectives, such as investigations into astrobiology, atmospheric science, medicine, and geoscience.

With capabilities to travel to Mars, it will be possible to visit some asteroids in their native orbits. These remnants of early Solar System formation have scientific interest and may hold resources which will be useful in the future.

Science opportunities at Near-Earth Asteroids

Near-Earth asteroids exhibit considerable diversity within their population and have witnessed events and conditions throughout the history of the Solar System. Human exploration of asteroids will permit placement of complex instruments on the asteroid surface, as well as the ability to sample surface and subsurface sites to obtain information on the ancient history of the Solar System that larger and evolved planetary bodies have lost. Samples that are carefully chosen by a trained explorer can also help us better understand the thousands of meteorites we already have available for study by scientists, providing geologic context to meteorites that have formed much of the paradigm for the origin of the Solar System. We will also work to better understand the internal structures of Near-Earth Asteroids, a vital part of the puzzle needed in order to develop mitigation strategies for addressing threats from an Earth-bound asteroid.

Robotic Exploration Missions

Planned future robotic missions to the Moon and Mars are important for answering new science questions and closing strategic knowledge gaps related to human space exploration. The agency-led missions referenced below will be joined by numerous other robotic missions and cubesats planned by public and private organisations. ISECG space agencies have worked with relevant groups to identify strategic knowledge gaps associated with the Moon, asteroids and Mars, which can be accessed at **www.globalspaceexploration.org**.

Future Lunar Robotic Missions

Mission	Agencies/Launch Date	Objectives/Strategic Knowledge Gaps Addressed
Chandrayaan-2	ISRO/2018	Polar scientific orbiter, lander, and rover.
Chang'E-4	CNSA/2018	Far side scientific lander and rover. Communications relay satellite.
Chang'E-5	CNSA/2019	Near side sample return.
KPLO	KARI/2020	Polar scientific orbiter.
Luna 25/Luna Glob	Roscosmos/2020	Lunar volatile prospecting. Soft landing technology demonstration.
SLIM	JAXA/2020	Technology demonstration.
Polar Sample Return	CNSA/around 2020	Polar volatiles sample return.
Luna 26/Luna-Resurs Orbiter	Roscosmos/2022	Polar scientific orbiter. Polar volatiles mapping.
Resource Prospecting Mission	NASA/early 2020's	Polar science, volatile prospecting and acquisition. Drill technology demonstration.
JAXA's Resource Prospector	JAXA/early 2020's	Polar lander and rover. Polar science and volatiles prospecting.
Luna 27/Luna-Resurs Lander	Roscosmos, with ESA/2023	Polar science, volatile prospecting and acquisition. Drill technology demonstration.
ISRU Demo	ESA/2025	ISRU technology demonstration.
Korea Lunar Lander	KARI	Technology demonstration.
Luna 28/Luna Grunt	Roscosmos	Cryogenic polar volatiles sample return.

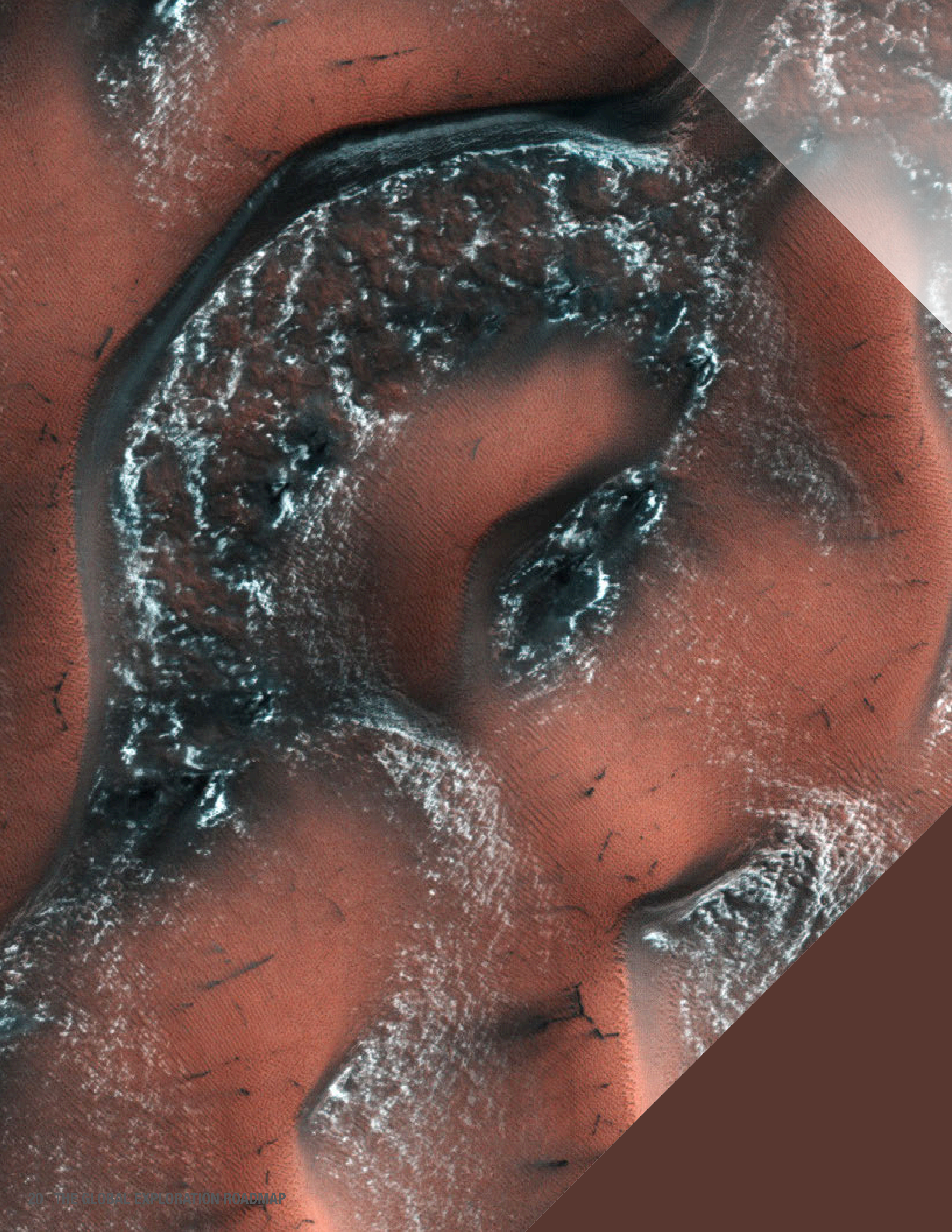
Mars Sample Return

Mars sample return is a high priority for the global planetary science community. It will advance our search for life in the Solar System. The mission will also address key decadal survey priorities and allow us to understand the mechanical properties of the soil/dust and potential health hazards. It will also inform techniques for roundtrip human missions.

Under NASA leadership, mission concepts are under study. At a conceptual level, a sequence of three missions is envisioned to collect samples, place them into Mars orbit, and return them to Earth. This modular approach is robust, with each mission possessing a manageable number of engineering challenges. The approach also allows the sample return campaign to proceed at a pace determined by available funding and international involvement. The study of Mars as an integrated system is so scientifically compelling that it will continue with future missions implementing geophysical and atmospheric networks, providing in-situ studies of diverse sites and ample opportunity for additional investigations to be accomplished before the arrival of humans to the surface of Mars.

Future Mars Robotic Missions

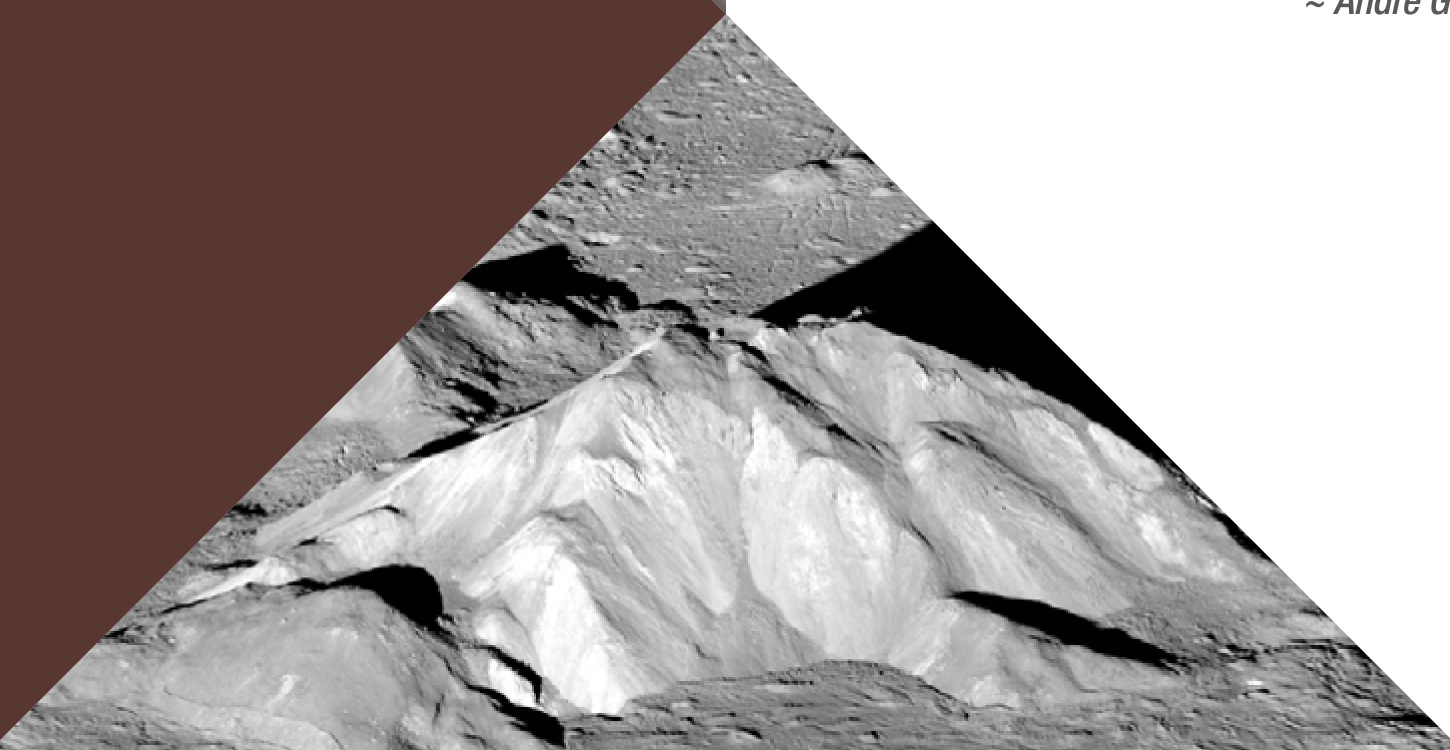
Mission	Agencies/Launch Date	Objectives/Strategic Knowledge Gaps Addressed
InSight	NASA, with CNES, CSA, DLR/2018	Subsurface geothermal gradient/seismology and internal structure of the planet. Identification of seismic risk at the location. Weather station to monitor weather conditions.
ExoMars	ESA/Roscosmos, with ASI, CNES, DLR, NASA, UKSA and Spain/2020	Rover with 1.5m drill with instruments to search for bio-signatures, subsurface hydrated materials and very shallow ice.
Mars 2020	NASA, with CNES, ASI, Norway and Spain/2020	Oxygen processing demonstration, caching samples for later return to Earth.
EMM Hope	UAE Space Agency/2020	Synoptic weather views moving through all times of day.
HX-1	China/2020	Orbit, landing and roving mission. Investigate topographical and geological features, physical fields and internal structure, atmosphere, ionosphere, climate and environment.
Mars Orbiter Mission-2	ISRO/2022	Orbiter to study the surface and sub-surface features, mineralogy composition and upper atmospheric processes.
Mars Moons eXploration	JAXA with CNES, NASA and other agencies/2024	Sample return from one of the two moons to progress our understanding of planetary system formation and primordial material transport.



Chapter 3: Preparatory Activities

"Man cannot discover new oceans unless he has the courage to lose sight of the shore."

~ André Gide



Private Sector Initiatives and Partnership Opportunities

The last five years have seen significant growth in private space exploration activities. Emerging commercial ventures, start-ups, small and medium enterprises, as well as large aerospace companies are aiming to benefit from increased interest and commercial potential as human presence in space is expanded. These developments are not limited to low Earth orbit. Numerous initiatives have early stage private funding to advance technologies and system concepts that will help make the exploration and economic development of the Moon, asteroids and eventually Mars, both affordable and achievable. For example, motivated by the Google LunarX Prize, several teams have developed small lunar landing and roving devices that represent capabilities which could be purchased to achieve commercial or space agency objectives. Asteroid mining concepts have illuminated the resource potential of these celestial bodies. These initiatives are a significant factor in government planning for future exploration. They present opportunities for public-private partnerships that will help achieve ambitious space exploration goals and objectives more cost effectively and contribute to affordability of the global space exploration endeavour.

Private sector innovation is a necessary component of making human space exploration sustainable and contributing to the opening of new markets and economic expansion.

Space agency planning for human exploration can already anticipate opportunities for public-private partnerships aimed at strengthening the missions defined in this roadmap. Looking one step beyond, the availability of commercial services and capabilities may influence architectures and mission approaches. For example, the ability to purchase propellant around the Moon, should it develop, will certainly impact exploration architectures. Agencies are interested in the following:

1. Space capability development partnerships that lead to the availability of capabilities or services supporting exploration missions:
   a. Cost-sharing to realise a capability or future service that would support government and other customers. Examples may include power, fuel supply, robotics assembly and servicing, lunar surface mobility, etc.
   b. Government contribution of technical expertise, facilities, hardware or software to the partnership

2. Commercial space services:
   a. Delivery of logistics to the deep space Gateway
   b. Communication services
   c. Delivery of instruments or logistics to the surface of the Moon and Mars

An international consensus exists on the value of government/private sector partnerships. Agencies welcome private sector efforts and the innovative ideas that result. Strengthening the space exploration community and promoting the development of new markets in space are keys to a sustainable human space exploration effort.

An illumination map of the resource-rich areas near the Moon's south pole. This map was created from thousands of images taken throughout a lunar year by NASA's Lunar Reconnaissance Orbiter.

In-Situ Resource Utilisation and the Lunar Poles

For several decades, the use of local resources at exploration destinations has been studied as a way to limit the cost and complexity of bringing all the needed supplies from Earth. Water is a high priority resource, as it can be used for life support consumables and the production of rocket propellant. While water exists on Mars and asteroids (as ice or in hydrated minerals), the nearness of the Moon and the presence of water ice at the lunar poles has placed the exploration for lunar polar volatiles as a high priority for ISECG agencies. Study of lunar volatiles also opens up new avenues of scientific research; such as where do the water and other volatiles come from? How did they become concentrated in the permanently shaded regions?

Other resources, including bulk regolith for construction and radiation shielding, solar-wind implanted gases, and the many chemicals and minerals that make up the surface materials on the Moon, Mars and asteroids may also be valuable for sustained long-term human presence.

Resource Prospecting

Finding useful resources and understanding their grade and tonnage is one of the important first steps in determining their potential.

ISECG agencies with lunar polar robotic missions are working on a coordinated strategy to explore multiple sites of high interest where orbital data indicates the presence of water ice. By targeting different sites on the lunar surface, the first missions to reach the lunar poles will take one or more of the measurements listed below to allow comparison of sites for their resource potential:

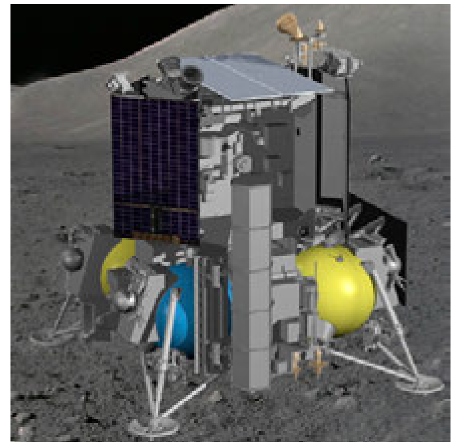
- Bulk Hydrogen within 1 m of the surface
- Volatile inventory
- Geological context
- Geotechnical and physical properties of the site

Subsequent missions could then conduct more intensive characterisation at the most promising sites, determining the grade and tonnage of water ice deposits. Space agency missions may be supplemented by targeted instrument delivery by commercially available lunar landers.

Resource Acquisition and Processing Demonstrations

Several upcoming robotic missions include capabilities to acquire and process local resources. Drills and science instruments on Roscosmos's Luna 27 and NASA's resource prospecting mission will demonstrate the thermochemical extraction of water from lunar regolith. ESA is also funding an ISRU demonstration mission with a commercial partner to produce water or oxygen on the Moon. NASA's Mars 2020 will collect the Mars atmosphere and then electrochemically split the CO_2 molecules into oxygen and carbon monoxide.

If the use of lunar volatiles and other space resources is proven to be economically advantageous, it is envisioned that commercial companies will collaborate with ISECG agencies in public-private partnerships to develop a space-based industry of in-situ resource utilisation.



Luna-27, near-term lunar polar volatiles prospecting mission.

Exploring and Using Lunar Polar Volatiles

ISECG space agencies have been working together to better understand the potential of lunar polar volatiles. International virtual workshops open to all have been held to share information and seek consensus on next steps. A website has been developed to share information on the current agency activities and a reference library. The website can be accessed at **https://lunarvolatiles.nasa.gov/**.

JAXA's Resource Prospector Mission is a mission under study.

Advanced Technologies

Each step in expanding human presence beyond low Earth orbit relies on the readiness of new capabilities and technologies. As no single agency has the resources to develop all those critical capabilities, appropriately leveraging global investments in technology development and demonstration is important. Although technology development is a competitive area, space agencies seek to inform their technology investment planning, create synergies and maximise their readiness to play a critical and visible part in the exploration endeavour.

Identification of Critical Technology Gaps: Space agencies have identified a list of critical technologies related to the missions shown in the Global Exploration Roadmap that are currently not available or need to be developed or matured. These technologies are considered technology "pulls" and can be mapped to corresponding agency technology development activities. By mapping critical technology needs to agency technology development activities, gaps can be identified. The Critical Technologies table shown on page 23 summarises many of the critical technology gaps. Technology needs for Mars vicinity/surface missions are the main driver and early availability of some of the technologies will enhance exploration of the lunar surface.

Assessing and Closing Technology Gaps: The listed critical technologies identify a large spectrum of challenges needed to close the gap between the state of the art and the technology required for the specific mission. The majority of these technologies are actively being pursued by multiple ISECG agencies with a robust level of investment and are envisioned to be sufficiently advanced by current or planned technology development activities. Several other technologies are advancing forward, but with more moderate levels of investment, meriting attention to ensure readiness. However, some critical technologies do not yet show a clear path to closure and need particular attention by the space exploration community and would benefit strongly from coordination and collaboration.

Detailed gap assessments of selected critical technologies have shown that:

- **Liquid Oxygen/Methane propulsion technologies** can make use of in-situ propellant production, lead to improved performance, and leverage fluid commonality. Technology gaps that need to be addressed include throttleable engines, thrusters with integrated cryogenic feed systems, long-duration reliable cryogenic refrigeration systems, and high performance pressurization systems that improve storage density and reduce mass.

- **Dust mitigation technologies** are a key enabling factor to perform extended duration lunar surface missions. While viable technology solutions have been identified by experts, there is a need for the maturation of related technologies to support both lunar and Mars missions. No single technology completely solves the challenges of dust, but rather a suite of technologies will be required to address them.

- **Autonomous systems** enable the crew to conduct operations under nominal and off-nominal conditions independent of assistance from Earth-based support. Advances in electronics, computing architectures and software that enable autonomous systems to interact with humans are needed and can be leveraged from commercial markets to support maturation of needed capabilities.

- **Tele-robotic operations with time delay** can make human-in-the-loop commanding and monitoring of robots at remote distances less effective. For safety and efficiency with time delays greater than five seconds, it is recommended that robots be operated as autonomously as possible. Terrestrial applications in this area are well advanced but on-orbit applications need to be matured.

Partnerships: Terrestrial commercial applications are well developed in several areas related to critical technologies. Fostering partnerships among government and commercial organisations will advance critical knowledge and accelerate the demonstration of spin-in technologies in space in order to verify the performance in a flight environment and identify unknown issues specific to operations beyond low Earth orbit. Partnerships can also lead to valuable experience and knowledge gap closures, especially in the development of standards and common interfaces.

CSIRO Autonomous Systems Research.

The following table highlights technologies identified by the ISECG as critical for future exploration missions. The target performance for each technology is based on preliminary analysis for human Moon and Mars missions, and may change as the analysis is iterated further. There are technologies where the state of the art is sufficient for near-term lunar operations and opportunities exist to demonstrate advancements needed for Mars. For the full Critical Technology Portfolio: **www.globalspaceexploration.org**

<table>
<tr><th>Global Exploration Roadmap Critical Technologies (Summary Table)</th><th>Today ISS & Spaceflight Heritage</th><th>Near-Future Moon Vicinity/Surface</th><th>Future Mars Vicinity/Surface</th></tr>
<tr><td colspan="4">Propulsion, Landing, Return</td></tr>
<tr><td>In-Space Cryogenic Acquisition & Propellant Storage</td><td>Spacecraft: CPST/eCryo demo</td><td colspan="2">u-G vapor free liquid tank to propulsion transfer, Efficient low-power LOx & H_2 storage >1 Yr (Mars)</td></tr>
<tr><td>Liquid Oxygen/Methane Cryogenic Propulsion</td><td></td><td>Throttleable Regen Cooled Engine for Landing (Lunar Scale)</td><td>Throttleable Regen Cooled Engine for Landing (Mars Scale)</td></tr>
<tr><td>Mars Entry, Descent, and Landing (EDL)</td><td>Spacecraft: MSL class (~900 kg)</td><td>Demonstration of advanced technology in deep space environment</td><td>Large Robotics >1000 kg; Human ~40,000 kg</td></tr>
<tr><td>Precision Landing & Hazard Avoidance</td><td>Spacecraft: Lunar & Mars Landers State-of-the-Art</td><td colspan="2">~100 m accuracy, 10's cm hazard recognition, Support all lighting conditions</td></tr>
<tr><td>Robust Ablative Heat Shield Thermal Protection</td><td>Spacecraft: Orion Heatshield test flight (EFT-1)</td><td>~1000 W/cm2 under 1.0 atmospheric pressure</td><td>~2,500 W/cm2 under 0.8 atmospheric pressure</td></tr>
<tr><td>Electric Propulsion & Power Processing</td><td>Spacecraft: 2.5 kW thruster (Dawn)</td><td>~10 kW per thruster, High Isp (2000 s) (for some mission options)</td><td>~30-50 kW per thruster (for some mission options)</td></tr>
<tr><td>Mid & High Class Solar Arrays</td><td>ISS: 7.5 kW/Panel</td><td>High Strength/Stiffness Deployable, 10-100 kW Class (for some mission options)</td><td>Autonomously Deployable, 300+kW Class (for some mission options)</td></tr>
<tr><td colspan="4">Autonomous Systems</td></tr>
<tr><td>Autonomous Vehicle System Management</td><td>ISS: Limited On-Board Mgmt functions, < 5 s comm delay</td><td>On-Board Systems Mgmt functions (handles > 5 s comm delay)</td><td>On-Board Systems Mgmt functions (handles > 40 min comm delay)</td></tr>
<tr><td>AR&D, Proximity Operations, Target Relative Navigation</td><td>ISS: Autonomous docking</td><td colspan="2">High-reliability, All-lighting conditions, Loiter w/ zero relative velocity</td></tr>
<tr><td>Beyond-LEO Crew Autonomy</td><td>ISS: Limited Autonomy</td><td colspan="2">Automate 90% of nominal ops
Tools for crew real-time off-nom decisions</td></tr>
<tr><td colspan="4">Life Support</td></tr>
<tr><td>Enhanced Reliability Life Support</td><td>ISS: MTBF <10 E-6, Monitored/operated by GC</td><td colspan="2">More robust & reliable components (eliminate dependence on Earth supply logistics)
Increased systems autonomy, failure detection capabilities, and in-flight repairability</td></tr>
<tr><td>Closed-Loop Life Support</td><td>ISS: 42% O_2 Recovery from CO_2, 90% H_2O Recovery</td><td>Demonstration of advanced technology in deep space environment</td><td>O_2/CO_2 Loop closure; H_2O Recovery further closure; Solid Waste, reduce volume/storage</td></tr>
<tr><td>In-Flight Environmental Monitoring</td><td>ISS: Samples to Earth</td><td colspan="2">On-Board Analysis for Air, Water, Contaminants</td></tr>
<tr><td colspan="4">Crew Health & Performance</td></tr>
<tr><td>Long-Duration Spaceflight Medical Care</td><td>ISS: First Aid+, return home</td><td>Demonstration of advanced technology in deep space environment</td><td>Training (pre & in-flight) for medical aspects
Continuous monitoring & decision support</td></tr>
<tr><td>Long-Duration Behavioral Health & Performance</td><td>ISS: Monitoring by Ground</td><td>Demonstration of advanced technology in deep space environment</td><td>Cognitive performance monitoring
Behavioral health indicators & sensory stim.</td></tr>
<tr><td>Microgravity Counter-Measures</td><td>ISS: Large treadmills, other exercise equipment</td><td>Demonstration of advanced technology in deep space environment</td><td>Compact devices to assess/limit disorders
Reduced weight/vol. aerobic & resistive eqpt.</td></tr>
<tr><td>Deep Space Mission Human Factors & Habitability</td><td>ISS: Large crew volume, food & consumables regular resupply</td><td>Demonstration of advanced technology in deep space environment</td><td>Assess human cognitive load, fatigue, health
Optimized human systems factors/interfaces</td></tr>
<tr><td>Space Radiation Protection (GCR & SPE)</td><td>ISS: Partially protected by Earth
Apollo: (accepted risk)</td><td colspan="2">Advanced detection & shielding
New biomedical countermeasures</td></tr>
<tr><td colspan="4">Infrastructure & Support Systems</td></tr>
<tr><td>High Data Rate (Forward & Return Links)</td><td>Ground (DSN): 256 kbs Forward, 10 Mbs Return Link</td><td>Demonstration of advanced technology in deep space environment</td><td>Forward: 10's Mbps; Return: Optical > 1Gb/s</td></tr>
<tr><td>Adaptive, Internetworked Proximity Communications</td><td>ISS: Limited capabilities</td><td>Demonstration of advanced technology in deep space environment</td><td>>10's of Mbps simultaneously between users
Multiple Modes; Store, Forward & Relay</td></tr>
<tr><td>In-Space Timing & Navigation</td><td>ISS: Limited to GPS range
Spacecraft: DSN Ranging</td><td>Demonstration of advanced technology in deep space environment</td><td>Provide high-spec Absolute & Relative pos'n
Space-Qualified clocks 10x-100x beyond SOA</td></tr>
<tr><td>Low Temperature & Long-Life Batteries</td><td>ISS: Lithium-ion (-156 C short duration), ~167 Wh/Kg</td><td>Lunar night temperatures and duration</td><td></td></tr>
<tr><td>Comprehensive Dust Mitigation</td><td>Apollo: limited 3 day crew ops
Rovers: limited mitigation</td><td colspan="2">Multiple Active & Passive technologies required
Significant advances in Life cycle</td></tr>
<tr><td>Low-Temperature Mechatronics</td><td>ISS: +121 to -157 C</td><td colspan="2">Operations to -230 C (cryo compatible); multi-year life</td></tr>
<tr><td>ISRU: Mars In-Situ Resources</td><td></td><td>Potential Test-Bed for Mars Forward, and enhance lunar missions</td><td>O_2/CH_4 generation from atmosphere
LOX/LH_2 generation from soil</td></tr>
<tr><td>Fission Power (Surface Missions)</td><td></td><td>Potential Test-Bed for Mars Forward, and enhance lunar missions</td><td>Fission Reactor (10's of kWe)</td></tr>
<tr><td colspan="4">EVA/Mobility/Robotic</td></tr>
<tr><td>Deep-Space Suit</td><td>ISS: EVA Ops at 0.3 Bar (4.3 Psid)</td><td colspan="2">EVA Ops at 0.55 Bar (~8 Psid), extended EVA lifecycle
On-Back regen CO_2 & humidity control, High Specific-Energy Batteries</td></tr>
<tr><td>Surface Suit (Moon & Mars)</td><td>Apollo: 3 day max (Lunar)</td><td>30 day min duration, improved lower torso mobility, dust tolerant</td><td>1 year+ duration, thermal insulation (CO_2 atmosphere)</td></tr>
<tr><td>Next Generation Surface Mobility</td><td>Spacecraft: Lunar and Mars Rovers State-of-the-Art</td><td colspan="2">Autonomous & Crewed capability, less Ground Control
Extended range, speed, payload; navigate soft/steep varying soils</td></tr>
<tr><td>Tele-robotic Control of Robotic Systems with Time Delay</td><td>ISS: <1-10 Sec delay for GC Ops
Spacecraft: Lunar/Mars Rovers</td><td>Few seconds to 10's of seconds
Dynamic environments w/variable delays & LOC</td><td>Up to 40 Minutes</td></tr>
<tr><td>Robots working side-by-side w/ crew</td><td>ISS: Limited (Robotic support to EVA)</td><td colspan="2">EVA control robots w/ no reliance on Ground Control
International standard & protocols</td></tr>
</table>

Managing Human Health and Performance Risks for Space Exploration

Long-duration missions and planetary operations entail numerous risks that must be understood and mitigated in order to maintain the health and productivity of crew members. The five human spaceflight hazards that need to be considered for any deep space exploration mission are:

1. Radiation – in deep space, radiation exposure is a top concern.
2. Isolation – psychological stress associated with limited space and group dynamics.
3. Distance from Earth – some operations in deep space, such as medical activities and procedures, are a challenge.
4. Gravity – The different levels of gravity will affect many of the human physiological systems.
5. Environment – hostile and closed environments will affect the overall living environment (e.g., toxicology, microbiology, etc.).

To address these challenges, agencies are actively performing studies in laboratories, ground analogues and on board the ISS and other flight platforms, including the deep space Gateway.

On the Ground

Isolation facilities are used for studies on behavioural performance. The facilities being used include the Human Exploration Research Analogue in Houston, Texas, and the Institute of Biomedical Problems Ground-based Experimental Complex in Moscow, Russia.

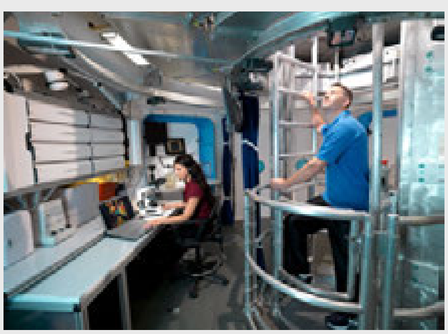
Other important ground facilities are located in Europe. These facilities host studies of musculoskeletal and cardiovascular deconditioning and psychological effects of long-term confinement. One example is the MEDES, an institute for space medicine and physiology in Toulouse, France.

In Flight

Numerous studies are ongoing onboard the ISS. Information on past and present studies can be found at **https://www.nasa.gov/mission_pages/station/research/** and **http://www.esa.int/Our_Activities/Human_Spaceflight/Research**.

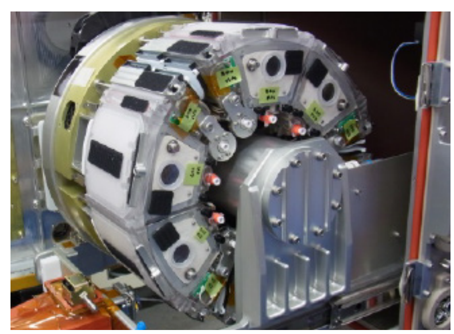
The first one-year mission has completed and preliminary results are interesting. Most notably, gene expression in space is altered, thereby opening new research possibilities aimed at mitigating health effects of long-duration spaceflight and with potential applicability to terrestrial health.

Today, bioanalytical and biomonitoring capabilities in space are limited. Canada is focusing on in-space analysis capabilities to remove these limitations. One example is a bioanalyser for space that can measure different populations of blood cells and measure diverse proteins in a single sample. This eliminates the need for storing samples and speeds the analysis. Another is a garment that can continuously collect an array of physiological data which is being developed for testing on ISS. An early version of this garment, Astroskin, has been used in isolation experiments on Earth. Canada is also developing a simple, robust technology to isolate biomolecules or cells of interest in order to enhance research capabilities on ISS and support science and medicine for future space exploration. Italy developed and positively tested on the ISS (VITA mission) a payload consisting in a garment containing water as shielding material against radiation, and a portable bioanalyzer enabling direct analysis of samples, rather than collecting and storing samples that will be analyzed upon their return to Earth.



NASA's Human Exploration Research Analogue is used several times per year to understand and test mitigation strategies for human performance risks.

Aquapad: During the ISS Proxima mission, CNES, in partnership with the bioMérieux company, tested a technology to detect microbial contamination of water. The technology, which is simple and can be stored in ambient conditions, has been used on Earth for the detection of cholera in high-risk locations.



JAXA's Multiple Artificial-gravity Research System is a rodent habitat for ISS. The system includes a centrifuge that allows studies from 0 g up to and including 1 g. This capability enables investigations comparing gravity effects on animals in the same space environment with gravity as the only variable.

Analogues to Simulate Exploration Destinations and Missions

In addition to analogues used for human health studies, other sites and facilities are in use today by space agencies around the world to simulate a variety of scientific, technical and operational activities in preparation for eventual exploration missions. Agencies are regularly sharing information related to planning of so-called “analogue” deployments and their associated lessons learned in order to maximise the usefulness of these activities.

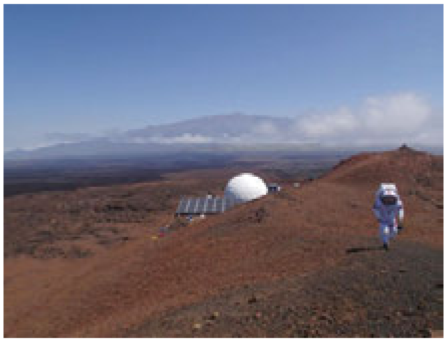
Technology Development Analogue Tests. Developing new technologies to accomplish the challenging missions in space can have the added benefit of stimulating new economic opportunities on Earth. The German Helmholtz Alliance “Robotic Exploration of Extreme Environments” (ROBEX) is one example of a collaboration between explorers from two different worlds – space and deep sea research. Sixteen research institutions, universities, and commercial companies cooperate to find solutions for autonomy, navigation, power management and communication for not only future lunar missions but also applications at the bottom of the world’s oceans.

DLR’s rover during the ROBEX analogue deployment on Mt. Etna, Italy.

Analogue Tests of Science Operations and Techniques. Achieving the goal of learning more about our place in the Universe will require human and robotic missions of increasing scope and complexity. In many cases, this leads to programs with significant international collaboration. One of the most complex and highly anticipated robotic missions on the horizon is the return of surface samples from Mars. The Canadian Space Agency recently completed a two-part analogue mission, the Mars Sample Return Analogue Deployment, simulating the sample caching and sample collection elements of this mission architecture. An international team of collaborators, including NASA/JPL, the UKSA, DLR, seven Canadian universities, and three American universities, participated in these deployments, involving simultaneous activities in both Canada and the United States.

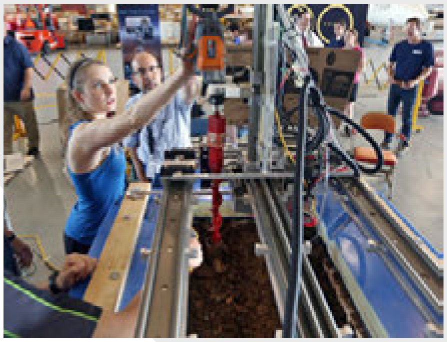
Training, Public Engagement, and Outreach. Agencies carry out many of their analogue missions in a way that can be readily grasped by the general public while acquiring meaningful information for the programs they support. Analogues are also being used to draw in the next generation of scientists and engineers to add a practical facet to classroom learning. The previously described Canadian analogue relied on a large contingent of students as an integral part of the accomplishing simulation goals. NASA’s Revolutionary Aerospace Systems Concepts – Academic Linkage program recently hosted a competition for engineering students to conceive and demonstrate innovative means for drilling into a simulated Martian ice deposit and withdrawing water—simulating new approaches to in-situ resource utilisation for future human missions—using approaches with a logical path to flight hardware. The two and one half days of the final competition was streamed live over the internet on a variety of platforms. This event generated over 1.5 million views on social media platforms.

Supporting Decisions Among Options. Analogues provide a cost-effective means of providing information to support strategic decisions: from top-level architecture options to lower-level system or subsystem options. For example, ESA’s Multi-Purpose End-To-End Rover Operations Network (METERON) experiment ANALOG-1 (scheduled for mid-2019) is designed to generate quantitative information supporting decisions regarding human-robotic coordinated operations, with a specific focus on the HERACLES mission.



HI-SEAS is a martian simulation on the slopes of the Mauna Loa volcano, Hawaii.

The CSA’s Mars Exploration Science Rover during the Mars Sample Return Simulation.

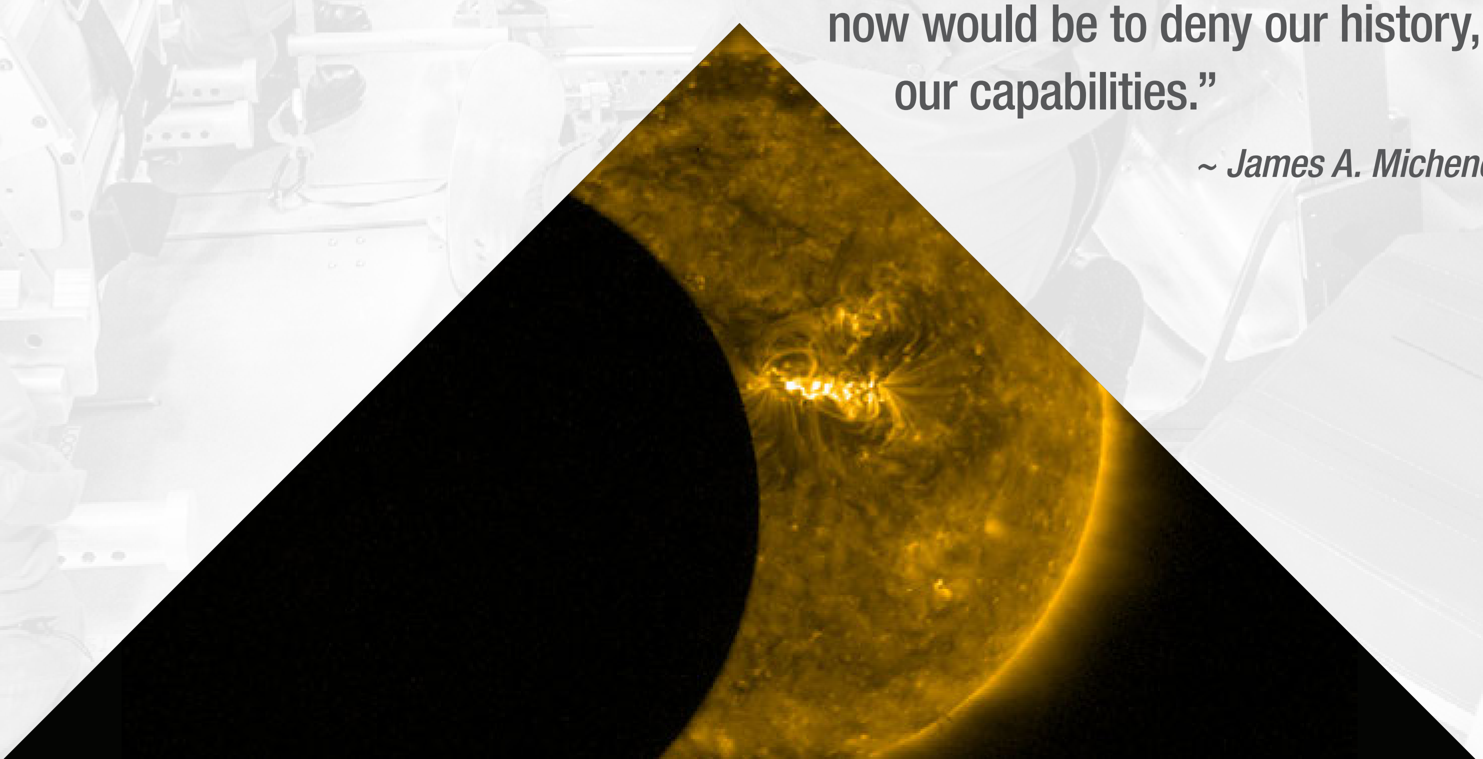


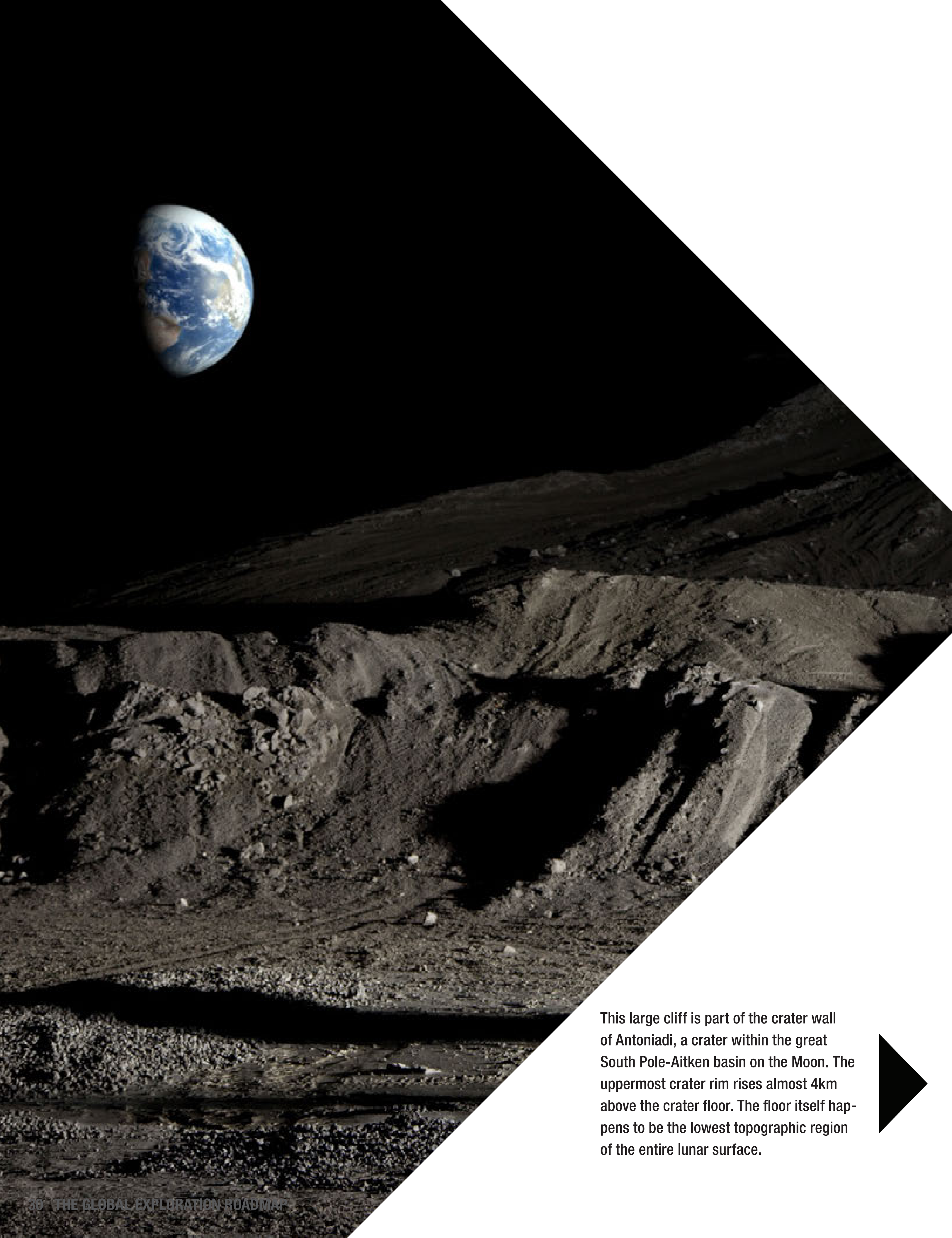
Revolutionary Aerospace Systems Concepts – Academic Linkage project engages students and the public.

Chapter 4:
Conclusion

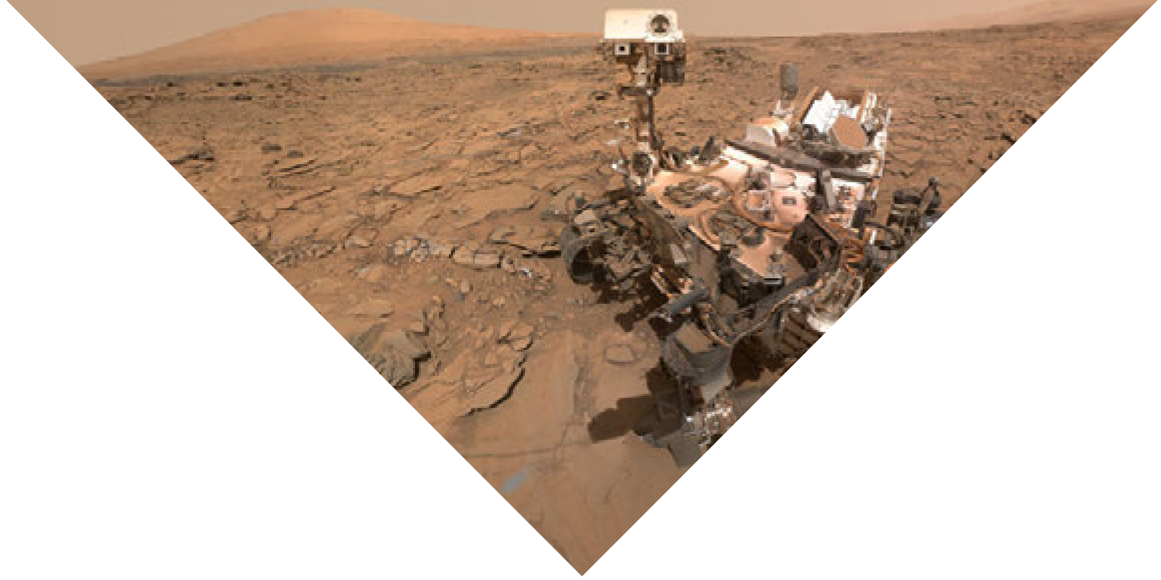
"Space is indifferent to what we do; it has no feeling, no design, no interest in whether or not we grapple with it. But we cannot be indifferent to space, because the grand, slow march of intelligence has brought us, in our generation, to a point from which we can explore and understand and utilise it. To turn back now would be to deny our history, our capabilities."

~ James A. Michener





This large cliff is part of the crater wall of Antoniadi, a crater within the great South Pole-Aitken basin on the Moon. The uppermost crater rim rises almost 4km above the crater floor. The floor itself happens to be the lowest topographic region of the entire lunar surface.



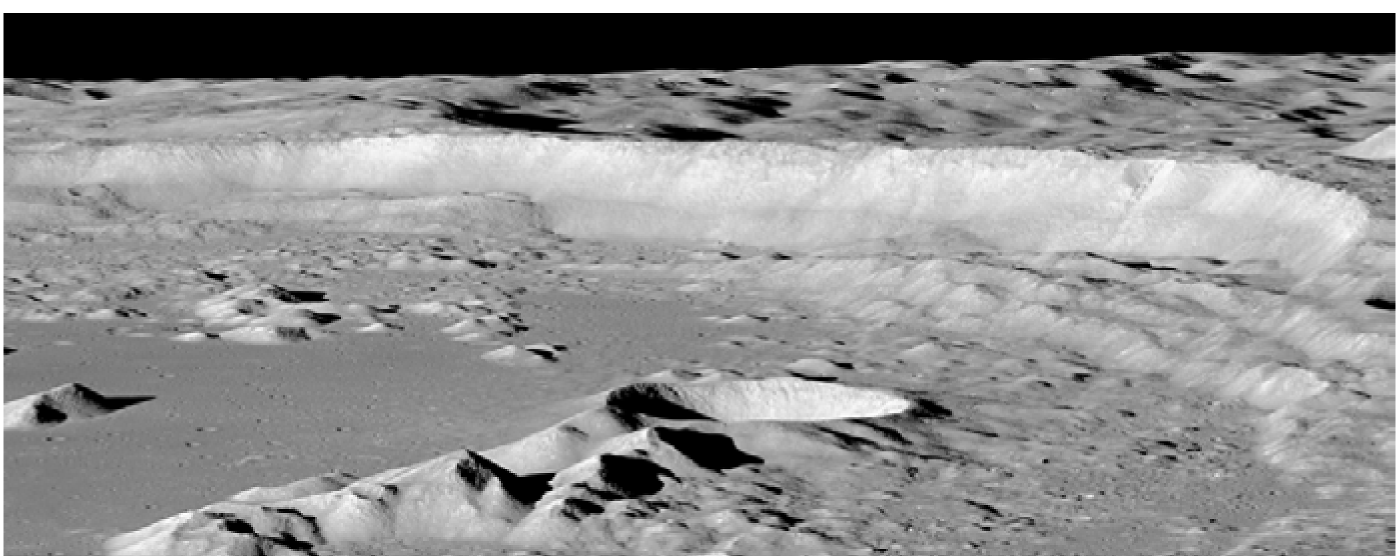
The Global Exploration Roadmap reflects international efforts to define a sustainable pathway for human exploration of the Solar System, with Mars as the horizon goal. International cooperation will not only enable these challenging missions, but also increase the probability of their success. Over time, updates to this roadmap will continue to reflect the efforts of space agencies to collaboratively develop exploration mission scenarios and coordinate their preparation.

Since its inception, space exploration has produced numerous benefits for humanity. Innovation and economic growth have resulted from efforts to solve the challenges of space exploration. Knowledge gained has driven scientific and technological innovation that continues to contribute to new products and services for spaceflight and terrestrial application. Space exploration stimulates curiosity about our place in the Universe, impacts culture, and inspires people on Earth. Overcoming the challenges and realising the capabilities needed to explore will bring nations together with the capacity to address shared challenges and opportunities.

Decisions regarding implementation of specific mission scenarios will follow national policy decisions and international consultation, but these decisions will be more durable and effective if informed by products (architectures, mission designs, etc.) developed collectively. International standards will enable multiple partners to participate. In the coming years, many nations will continue developing domestic policy, regulatory and legal frameworks to most effectively implement sustainable human space exploration.

Increasingly, space agencies are engaged in dialogue with private sector entities that are beginning to move forward with plans to invest in projects in and beyond low Earth orbit. For such private sector efforts to succeed, they need the certainty of a long-term governmental commitment to space exploration, the continued opportunity to introduce ideas into government thinking, and supportive national business environments.

While this document does not create commitments of any kind on behalf of any of the participants, the Global Exploration Roadmap and the coordination that supports its development are important tools for achievement of a global, strategic, coordinated, and comprehensive approach to space exploration. This and subsequent editions of the Global Exploration Roadmap will provide a technical basis to inform programmatic discussions among agencies. The space agencies participating in the ISECG will continue the dialogue to coordinate and advance sustainable space exploration, extending human and robotic presence into the Solar System.



ISECG
International Space Exploration
Coordination Group

The Global Exploration Roadmap is a nonbinding product of the International Space Exploration Coordination Group (ISECG) space agencies. This third edition will be followed by periodic updates as the content evolves and matures. ISECG is committed to the development of products that enable participating agencies to take concrete steps toward partnerships that reflect a globally coordinated exploration effort.

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