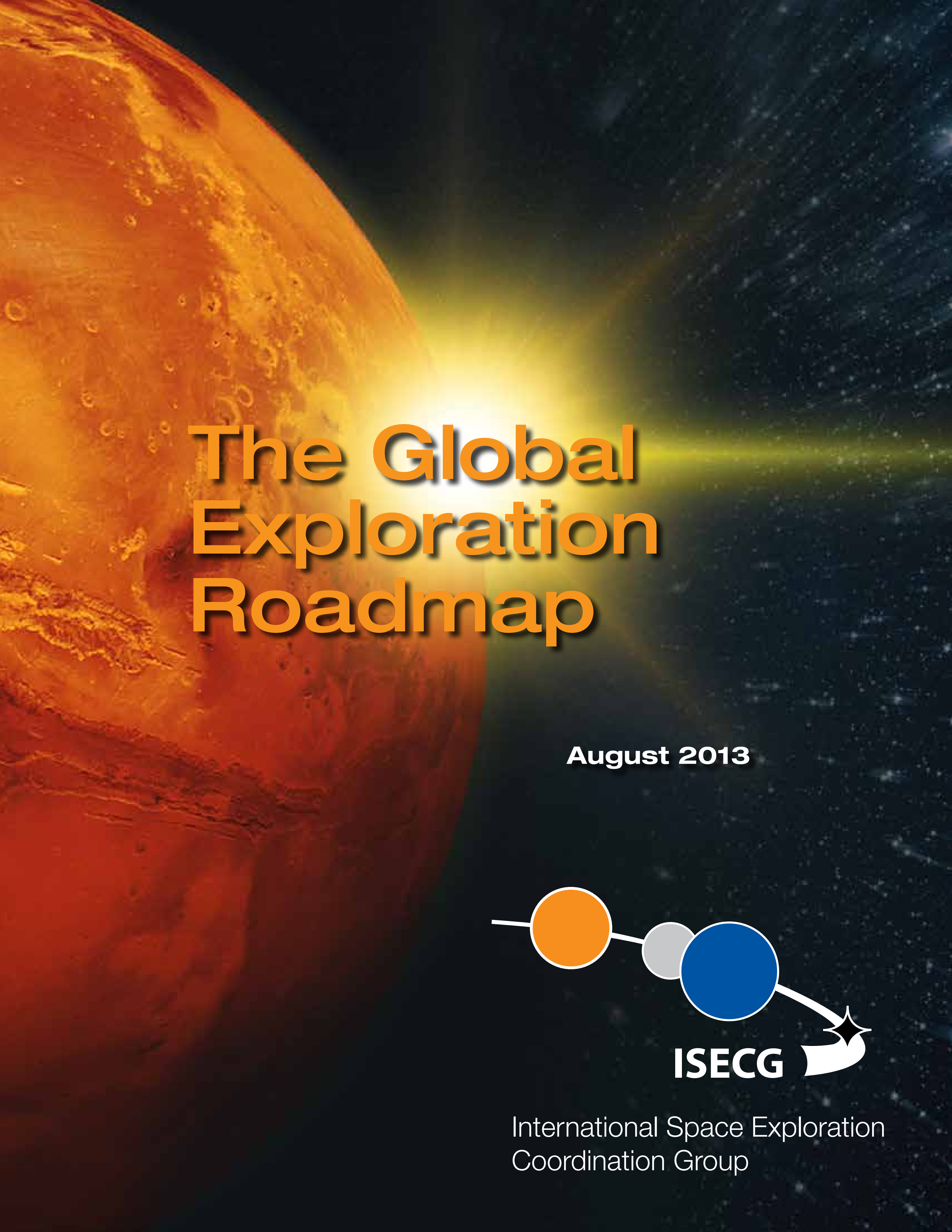
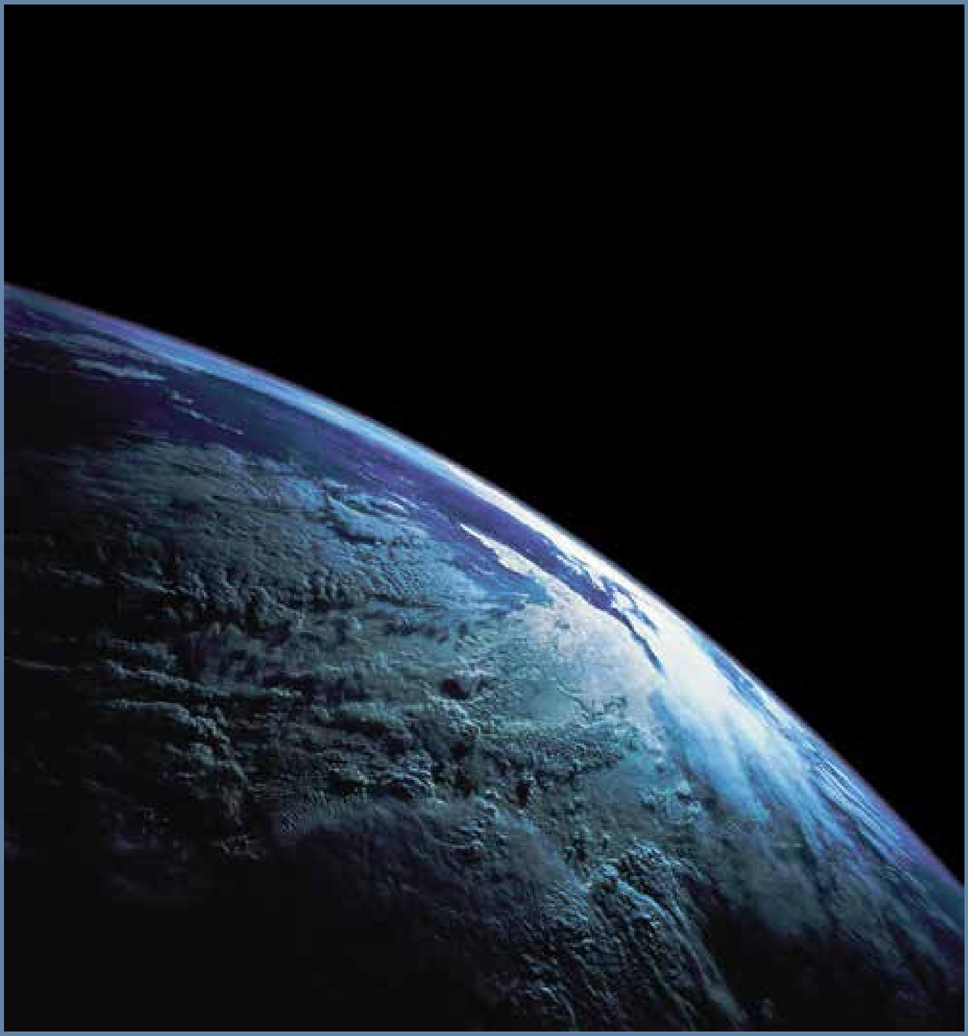


The Global Exploration Roadmap

August 2013

ISECG

International Space Exploration Coordination Group



"The surface of the Earth is the shore of the cosmic ocean.
From it we have learned most of what we know.
Recently, we have waded a little out to sea, enough to dampen our toes or,
at most, wet our ankles.
The water seems inviting. The ocean calls."

— Dr. Carl Sagan

The Global Exploration Roadmap

The Global Exploration Roadmap is being developed by space agencies participating in the International Space Exploration Coordination Group (ISECG). The roadmap builds on the vision for coordinated human and robotic exploration of our solar system that was established in *The Global Exploration Strategy: the Framework for Coordination (May 2007).* In doing so it reflects a coordinated international effort to prepare for collaborative space exploration missions beginning with the International Space Station (ISS) and continuing to the Moon, near-Earth asteroids, and Mars. Space agencies agree that human space exploration will be most successful as an international endeavour, given the challenges of these missions. Agencies also agree that pursuing this endeavour will deliver significant social, intellectual and economic benefits to people on Earth. This document presents the status of the space agency exploration road mapping activity. By sharing the results of this work with the broader community, space agencies seek to generate innovative ideas and solutions for meeting the challenges ahead.

International Space Exploration Coordination Group ISECG

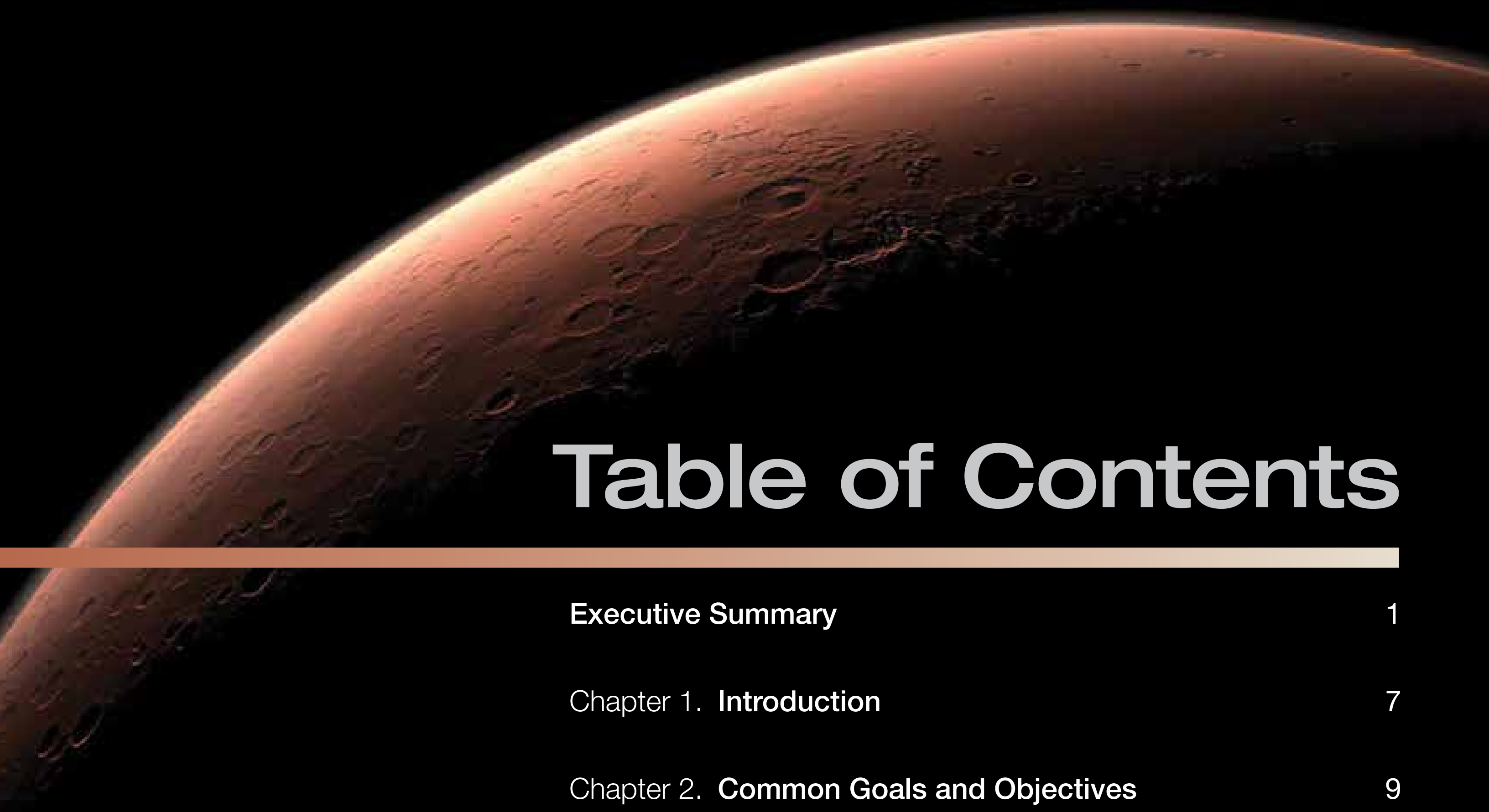
What is New in the Global Exploration Roadmap?

The initial release of the Global Exploration Roadmap in September 2011 provided an opportunity for stakeholders across the globe to engage in national and international dialogue about space exploration to destinations where humans may someday live and work. Ideas and feedback generated through this dialogue have strengthened agency planning efforts and led to some of the changes included in this version.

The initial roadmap identified two potential pathways toward the driving goal of human exploration of Mars: “Asteroid Next” and “Moon Next.” Each pathway was expanded through conceptual mission scenarios, which served as references to inform preparatory activities. Building on this work, the 2013 roadmap includes a single reference mission scenario that reflects the importance of a stepwise evolution of critical capabilities which are necessary for executing increasingly complex missions to multiple destinations, leading to human exploration of Mars. The roadmap demonstrates how initial capabilities can enable a variety of missions in the lunar vicinity, responding to individual and common goals and objectives, while contributing to building the partnerships required for sustainable human space exploration.

Participating space agencies continue to prepare for human exploration beyond low-Earth orbit. The expanded chapter on preparatory activities reflects accomplishments in the five original areas: ISS utilization, robotic missions, advanced technologies, next generation capabilities, and analogues. A sixth section has been added, focusing on human health and performance risk mitigation.

Italy
France
Canada
Germany
European Space Agency
India
Japan
Republic of Korea
United States
Ukraine
Russia
United Kingdom



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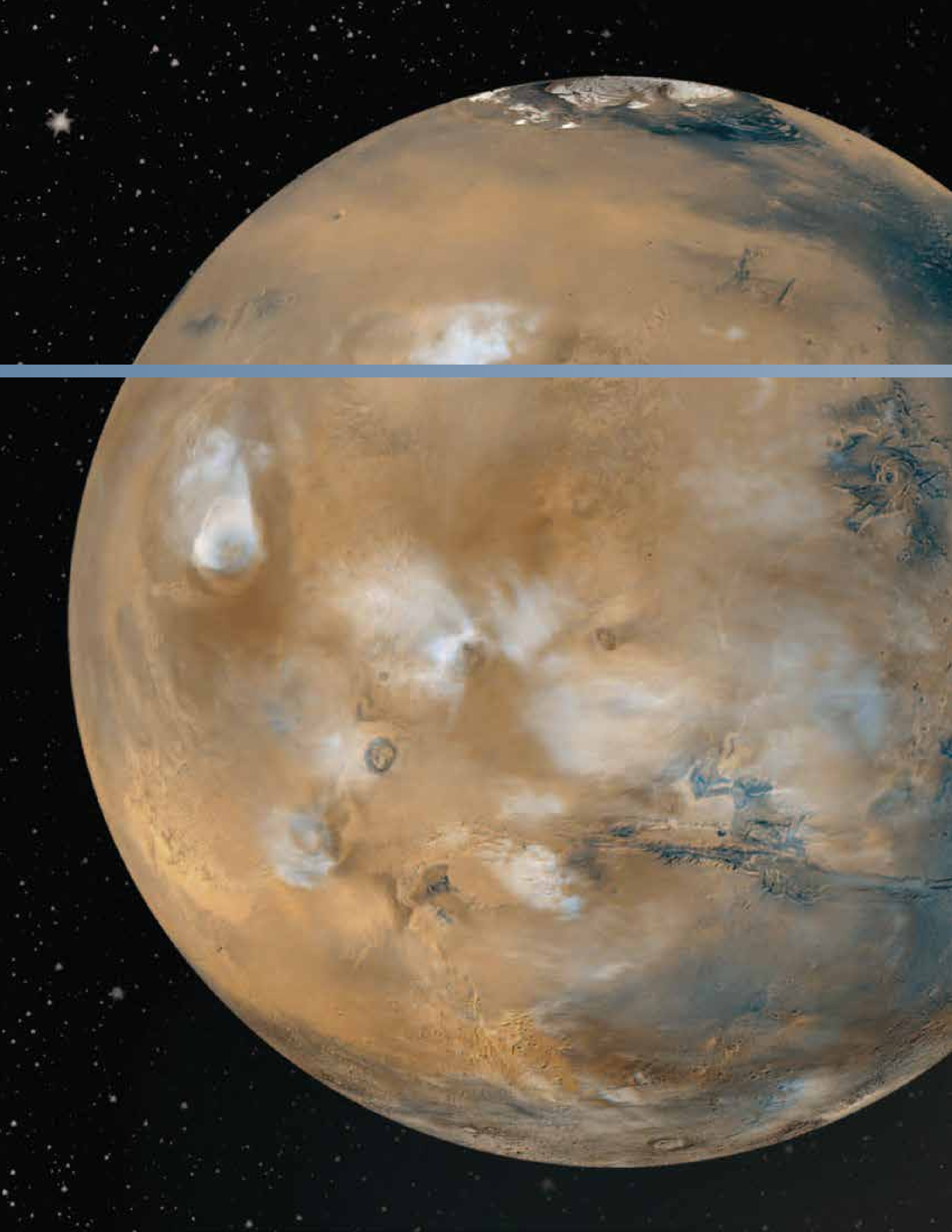
Daybreak over Gale Crater, Mars, the home to Curiosity since August 2012



Executive Summary

The Global Exploration Roadmap highlights the efforts of agencies participating in the ISECG to prepare for human and robotic exploration of destinations where humans may someday live and work. Enabling humans to explore the surface of Mars in a manner that is sustainable, affordable, and productive is a long-term goal that we will use to help shape our near-term activities. This goal informs capability evolution and technology investments. The pathway to Mars extends human presence to enable exploration of multiple destinations, including the Moon and near-Earth asteroids.

The Global Exploration Roadmap creates a framework for interagency discussions in three areas: 1) common goals and objectives, 2) a long-range human exploration strategy, and 3) coordination of exploration preparatory activities. By understanding the elements common to their exploration goals and objectives, and by collaborating to examine potential long-range scenarios, agencies continue to inform near-term decisions affecting their exploration preparation and to create opportunities for the partnerships which will realize future missions.

Global Exploration Roadmap

The roadmap reflects a common long-range human exploration strategy that begins with the ISS and expands human presence into the solar system, leading to human missions on the surface of Mars. It focuses on the first steps in implementing this strategy: utilizing the ISS, continuing to expand the synergies between human and robotic missions, and pursuing discovery-driven missions in the lunar vicinity that evolve capabilities and techniques needed to go further. By taking these first steps, missions into deep space and the Mars system would be enabled in a sustainable manner.

International Space Station

The ISS provides the opportunity for research and technology demonstrations which benefit from its unique location. It is also the foundation of exploration, advancing critical capabilities to take humans further into space and reducing the cost of human space flight.

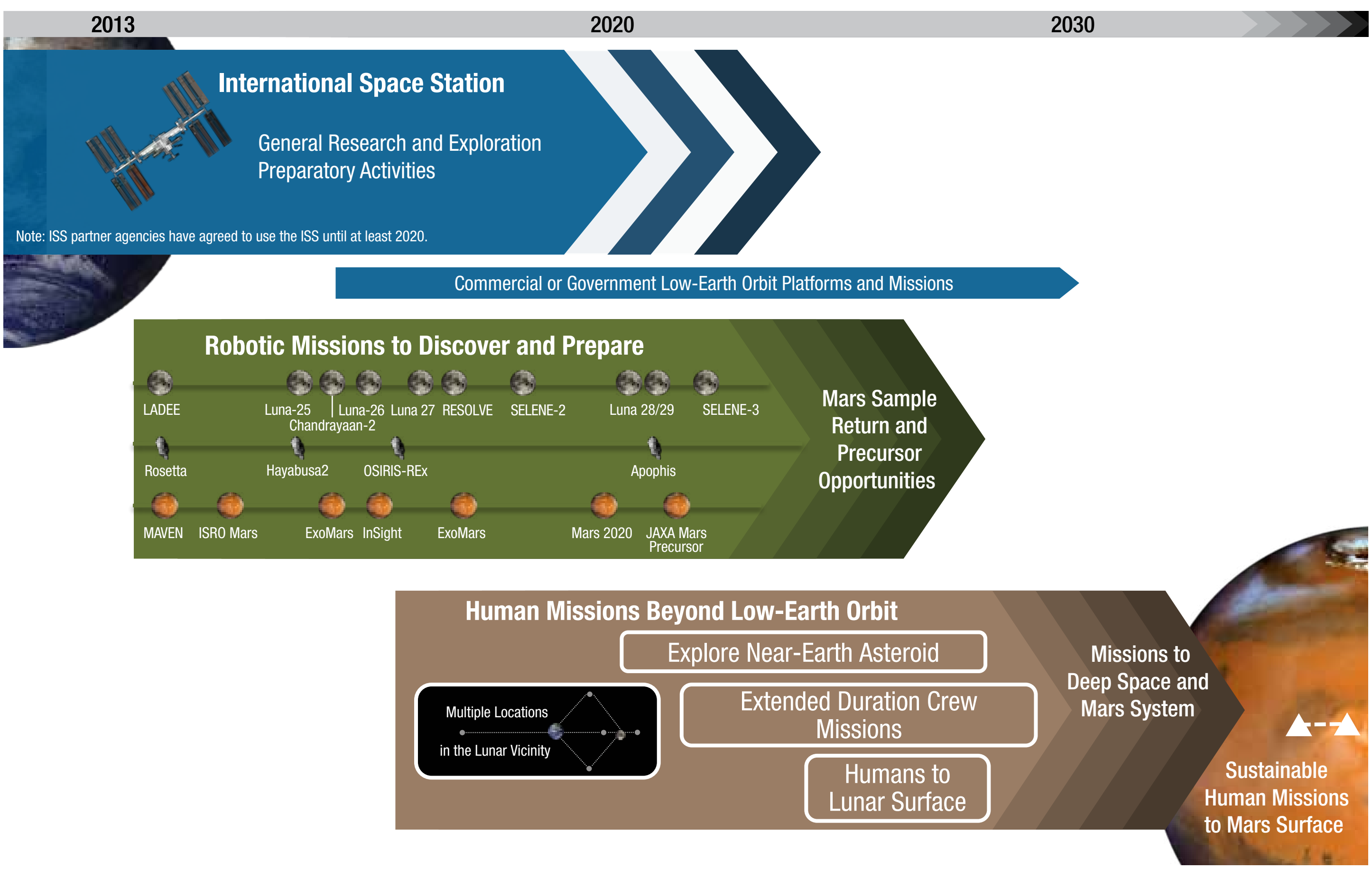
Robotic Missions to Discover and Prepare

Expanding on synergies between human and robotic missions will increase the unique contribution of each to achieving exploration goals and objectives. Robotic missions will provide new discoveries and serve as precursors to human exploration, contributing knowledge of the Moon, asteroids and Mars that will make subsequent human missions safer and more productive.

Human Missions Beyond Low-Earth Orbit

Human missions in the lunar vicinity and on the lunar surface would allow international partners to advance the capabilities needed for future Mars missions, while using the presence of the crew to explore the Moon and near-Earth asteroids. Missions to Mars will need reliable transportation, habitation, and other critical capabilities which can be advanced in the lunar vicinity and at the surface of the Moon. Deep space missions will be defined in the future, informed by new discoveries and enhanced by new technologies.

Global Exploration Roadmap



Common Goals and Objectives

The Global Exploration Roadmap is driven by a set of goals and supporting objectives that reflect commonality while respecting each individual agency's priorities. They demonstrate the rich potential for exploration of each of the target destinations, delivering benefits to people on Earth. The definitions listed below remain largely unchanged and demonstrate the synergy between science and human exploration goals and objectives.

ISS Commander Chris Hadfield communicates the significance of research activities on board the station.

Manufacturing has begun on the JAXA's Hayabusa2 flight article that is scheduled to launch in 2014.

Robo-Ops is an example of how planetary surface exploration challenges engage the minds of students around the world.

ESA's Mars Express image of the Reull Vallis region of Mars, showing a river-like structure that stretches for almost 1,500 km and is believed to have been formed long ago by running water.

Develop Exploration Technologies and Capabilities
Develop the knowledge, capabilities, and infrastructure required to live and work at destinations beyond low-Earth orbit through development and testing of advanced technologies, reliable systems, and efficient operations concepts in an off-Earth environment.

Engage the Public in Exploration
Provide opportunities for the public to engage interactively in space exploration.

Enhance Earth Safety
Enhance the safety of planet Earth by contributing to collaborative pursuit of planetary defense and orbital debris management mechanisms.

Extend Human Presence
Explore a variety of destinations beyond low-Earth orbit with a focus on continually increasing the number of individuals that can be supported at these destinations, the duration of time that individuals can remain at these destinations, and the level of self-sufficiency.

Perform Science to Enable Human Exploration
Reduce the risks and increase the productivity of future missions in our solar system, characterizing the effect of the space environment on human health and exploration systems.

Perform Space, Earth, and Applied Science
Engage in science investigations of, and from, solar system destinations and conduct applied research in the unique environment at solar system destinations.

Search for Life
Determine if life is or was present outside of Earth and understand the environments that support or supported it.

Stimulate Economic Expansion
Support or encourage provision of technology, systems, hardware, and services from commercial entities and create new markets based on space activities that will return economic, technological, and quality-of-life benefits to all humankind.

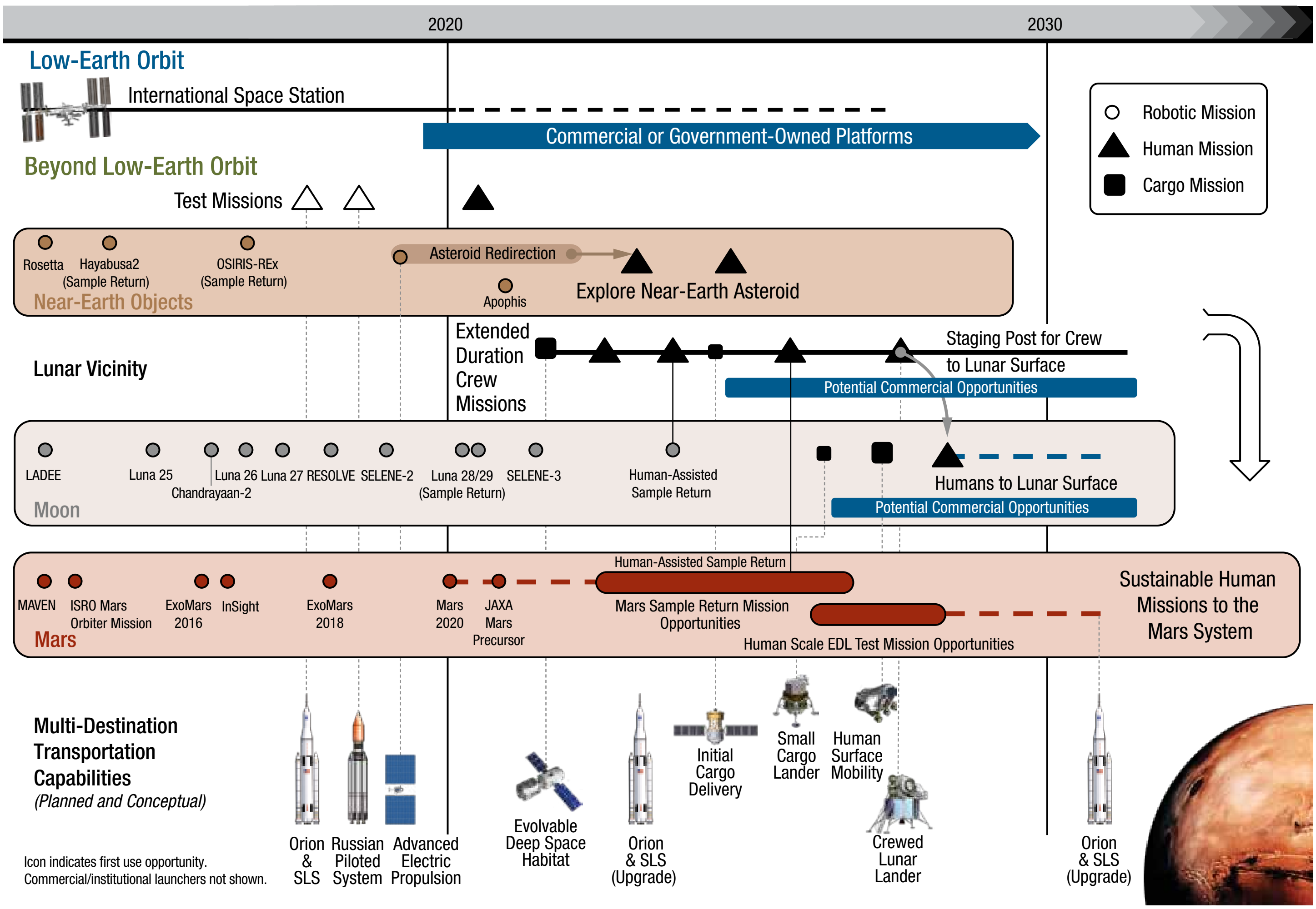
A Long-Range Human Exploration Strategy

By examining various pathways to Mars, agencies have continued to study capabilities which are required for human missions beyond low-Earth orbit. The ISECG Mission Scenario reflects a coordinated international effort to advance common goals and objectives while enabling interested agencies to pursue their priorities and prepare for critical contributions to Mars missions. All nations will not necessarily participate in every element or mission depicted in this roadmap. Sustainable human exploration missions to Mars will be possible if multiple agencies contribute capabilities and expertise. In addition, long-term sustainability may also be enhanced through availability of commercial services and use of public-private partnerships.

Using planned and conceptual capabilities, the ISECG Mission Scenario identifies a set of missions in the lunar vicinity and on the lunar surface that advance readiness for human Mars missions after 2030. Extended duration crew missions in the lunar vicinity and missions to an easily accessible asteroid will enable discoveries and allow demonstration of the transportation, habitation, robotic servicing and other key systems on which long-duration missions into deep space must rely. Human missions to the lunar surface will allow critical demonstrations of planetary exploration capabilities and techniques, while pursuing the highest priority lunar science objectives.

This mission scenario promotes the integration of robotic and human missions for achieving common objectives and developing concepts for increased human-robotic partnership. The ISECG Mission Scenario serves as a reference for agencies by informing studies and other exploration preparatory activities.

ISECG Mission Scenario



Human Exploration Preparatory Activities

Across the globe, engineers and scientists are working on many of the essential preparatory activities necessary to extend human presence further into space. By developing a common roadmap, agencies hope to appropriately coordinate their current investments, and work together in ways that maximize return on investments and enable earlier realization of their goals and objectives. Significant activities are underway in the following areas, each presenting opportunities for coordination and cooperation.

Use of the ISS for Exploration

The ISS is an excellent platform on which to prepare for future exploration missions. New activities in the areas of exploration technologies, human health research and operations simulations have been identified, and many have begun operation on board the ISS. Critical capabilities used to support the ISS will be advanced toward exploration requirements, such as lower mass, lower power and higher reliability.

Robotic Missions

Precursor robotic missions are essential for filling strategic knowledge gaps related to safe and successful human missions and for ensuring maximum return on the investments required for subsequent human exploration. Activities to increase the synergy between human and robotic missions driven by science and human exploration goals remain a high priority.

Advanced Technology Development

No single agency can invest robustly in all the needed technology areas that represent key challenges for executing human missions beyond low-Earth orbit. Creating opportunities for appropriate leveraging of global investments in technology development and demonstration has been a focus of participating agencies.

Development of New Space Systems and Infrastructure

Human exploration beyond low-Earth orbit will require a new generation of capabilities and systems which build on existing capabilities and incorporate technologies still to be developed. Significant progress continues to be made preparing human transportation systems for initial test flights while other key capabilities continue to be studied by interested agencies.

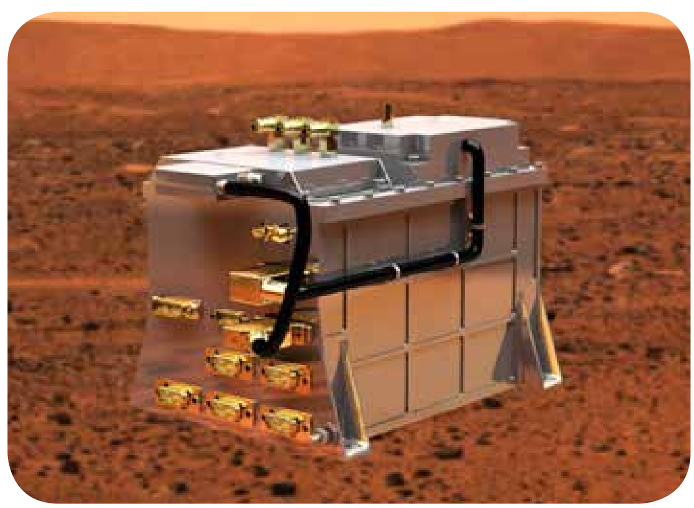
Analogue Activities

Testing in a relevant environment allows refinement of system designs and mission concepts, helping prepare for exploration beyond low-Earth orbit. Agencies are sharing lessons learned and plans for future analogue campaigns in order to gain maximum benefit from these activities.

Managing Health and Human Performance Risks

Long duration missions and surface operations present numerous risks to crew health and performance. Agencies are actively studying these effects and possible mitigation techniques, such as countermeasures and biomedical diagnostics, but much work remains to be done.

NASA's Orion spacecraft under test in preparation for the test flight in 2014.



ASI is developing the DREAMS (Dust characterization, Risk assessment and Environment Analyzer on Martian Surface) instrument suite to help characterize Mars landing site environments.

Conclusion

The Global Exploration Roadmap demonstrates that progress continues to be made in the effort to prepare for future exploration missions. Human exploration of the Moon, asteroids and Mars will strengthen humanity's future, bringing nations together in a common cause, revealing new knowledge, inspiring people, and stimulating innovation. As more nations undertake space exploration activities, they see the importance of partnering to achieve their objectives. This document is an international roadmap, following a path that allows interested nations to advance their capabilities in a stepwise fashion toward critical roles on human missions to Mars. It reflects consensus that addressing the challenges of exploring space will require the best efforts of all stakeholders, governmental and non-governmental.

The following observations are made to assist in this effort:

1. In order to build a sustainable human space exploration endeavour that lasts decades, agency leaders should maintain a focus on delivering value to the public.

2. With the goal of enabling several partners to contribute critical capabilities to future human missions, agencies note that near-term collaborative missions on the ISS, in the lunar vicinity, on the lunar surface, and robotic missions may be used to simulate and better inform preparations for future international missions to Mars.

3. New mission concepts, such as human-assisted sample return and tele-presence should be further explored, increasing understanding of the important role of humans in space for achieving common goals.

4. Robotic science missions provide an important technique for obtaining the data needed to prepare for human exploration beyond low-Earth orbit. It is generally accepted by both the science and exploration communities that measurements and data sets obtained from robotic missions support both the advancement of science and preparation for human exploration.

5. Agencies should increase efforts to pursue a coordinated approach to mitigating the human health and performance risks of extended duration exploration missions, putting priority on efforts to reduce countermeasure mass and volume, and on driving risks to an acceptable level.

The Global Exploration Roadmap facilitates the dialogue between human space flight, science, education and other space exploration stakeholder communities to advance a coordinated space exploration roadmap that addresses their highest priority goals and objectives. Collaborative work on the conceptual ISECG Mission Scenario will strengthen space exploration planning and ensure that the complementary capabilities of both humans and robotic systems enable humankind to meet the most ambitious space exploration challenges. The roadmap can serve to strengthen governmental support for international cooperation in human and robotic space exploration and provide the technical basis for informing necessary agreements among agencies and governments.

The Circumferential Dome Weld Tool, located at NASA's Michoud Assembly Facility in Louisiana, will be used to create the SLS core stage domes out of 12 panels.

Chapter 1.
Introduction

Since the first release of the Global Exploration Roadmap in September 2011, agencies have been making progress toward space exploration goals. They have planned and launched robotic missions, carried out new experiments on the ISS, and advanced new technologies and capabilities. Much work remains to be done to define implementable plans. By updating the roadmap, the participating agencies hope it can continue to inform the activities necessary to realize the vision of coordinated human and robotic exploration of destinations where humans may one day live and work.

Stakeholder engagement with the roadmap, whether conducted in a coordinated international manner or by agencies individually, has generated many innovative ideas and constructive feedback. This feedback has been taken into account in this update of the roadmap.

Exploring Together

Achieving the vision of sustainable human space exploration, including human missions to Mars, will require political commitment and resource availability over an extended period of time. History has repeatedly shown that finding ways to meet the challenges of safe and sustainable human space flight results in solutions with applications much broader than space flight. Benefits are derived from the achievements of human and robotic missions. They also result from the many activities associated with the mission that take place along the path to launch. It is important to ensure consistent realization and broader dissemination of the benefits generated by all space exploration activities.

Although human exploration of the surface of Mars presents complex technological and human performance challenges, progress continues to be made. The pathway to Mars begins with the ISS. Exploration preparation activities such as technology demonstrations, human health research, and operations simulations are being conducted. Advancing habitation and other critical systems supporting the ISS contributes to reducing the risks associated with human missions beyond low-Earth orbit.

With the next generation of space transportation capabilities opening the door to missions beyond low-Earth orbit for the first time since Apollo, missions in the vicinity of the Moon can provide needed opportunities for learning to operate effectively beyond the relative comfort of low-Earth orbit. These missions strengthen and expand the partnerships that will enable sustainable human space exploration.

Using Mars missions as a long-term driving goal, the ISECG Mission Scenario defines a stepwise evolution of human exploration capabilities that advance exploration of the Moon and a near-Earth asteroid. Capabilities which enable lunar surface exploration advance the readiness of partners for Mars surface missions. Continuous human presence on the Moon may follow, driven by government or non-government rationale, using existing and additional capabilities.

The ISECG Mission Scenario provides a framework to facilitate discussion on mission concepts and innovative ideas for meeting exploration challenges. It is considered technically feasible and programmatically implementable, creating opportunities for capabilities developed by various providers to enable exciting missions that meet shared goals and objectives.

The exploration of space, initiated more than 50 years ago, has contributed to enabling successful commercial activities in Earth orbit related mainly to communication, navigation, and Earth observation satellites. In recent years, commercial industry has continued to invest in space transportation and exploration services in response to government demands, incentive prizes, or simply to offer new services to the public. Several private ventures seeking commercial opportunities beyond low-Earth orbit have been initiated. The Global Exploration Roadmap recognizes that sustainable exploration must actively encourage new services and markets. Just as Earth orbit has been established as an important economic sphere, the same potential exists at future exploration destinations. The success of cargo delivery missions to the ISS demonstrates the feasibility of establishing public-private partnerships to stimulate the future availability of commercial services.

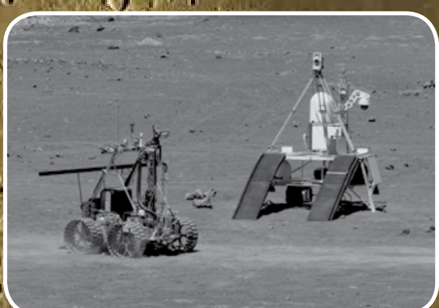
The Global Exploration Roadmap is an important tool for agencies in preparing for future roles and in seeking stakeholder feedback. The roadmap facilitates the agencies' preparation of exploration activities, allowing them to demonstrate to stakeholders the coherence of their proposals and plans in a broader international context.

The need to make human space flight more affordable continues to drive changes in the way agencies develop and operate space systems. The ISS partners are pursuing initiatives which lower the cost of operating the ISS and travelling to and from it. These initiatives should drive innovations which benefit exploration beyond low-Earth orbit. Innovations in research and technology are also essential. Success will come from finding innovative solutions to exploration challenges and pursuing the activities and partnerships which enable the best ideas to be realized.

Observation:

- ➔ In order to build a sustainable human space exploration endeavour that lasts decades, agency leaders should maintain a focus on delivering value to the public.

Chapter 2. Common Goals and Objectives of Space Exploration



Development of a Global Exploration Roadmap should be based on a clear understanding of the outcomes expected by participating agencies. It is important that mission scenarios reflect what space agencies want to accomplish, as articulated by specific goals and supporting objectives of space exploration.

The Global Exploration Roadmap is driven by a set of common space exploration goals and supporting objectives defined collectively by participating space agencies. The formulation of goals and objectives is an iterative process that reflects ongoing refinements as agency priorities evolve. Since the release of the initial Global Exploration Roadmap, these goals have been widely communicated, building a solid basis for determining the specific objectives of individual missions beyond low-Earth orbit.

These goals and objectives reflect the integrated nature of science and exploration and also build on the synergies which exist between human and robotic space exploration missions. In planning future human missions it will be essential to understand and address the highest priority science objectives.

The common goals, listed in alphabetical order, are described below:

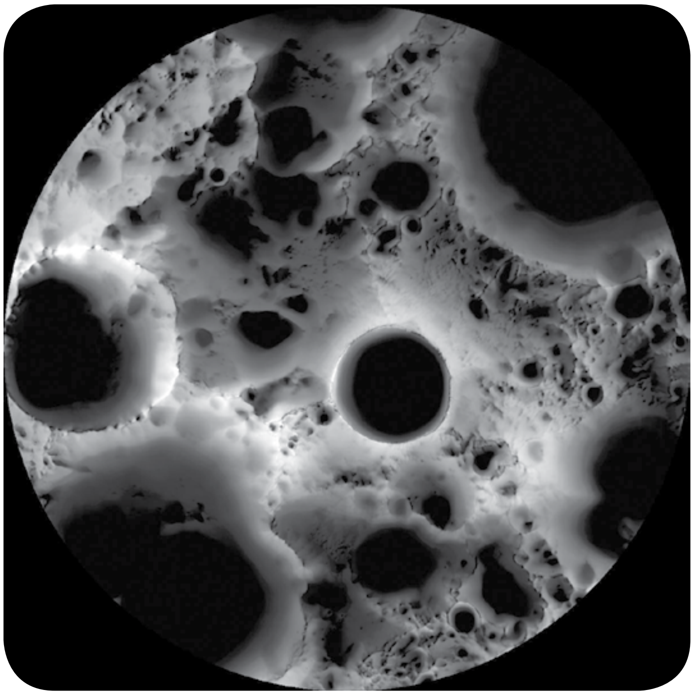
- **Develop Exploration Technologies and Capabilities.** Develop the knowledge, capabilities, and infrastructure required to live and work at destinations beyond low-Earth orbit through development and testing of advanced technologies, reliable systems, and efficient operations concepts in an off-Earth environment. Pursuing this goal also yields spinoff products, new materials and manufacturing processes, and various technologies that can address major global challenges.
- **Engage the Public in Exploration.** Space agencies have a responsibility to return value directly to the public that supports them by disseminating knowledge and sharing in the excitement of discovery. A participatory approach to exploration helps provide this value and maximizes opportunities to leverage public contributions to exploration missions. Pursuing this goal also creates opportunities to educate and inspire citizens, particularly young people, and to contribute to the cultural development of communities.

A meteorite contrail is seen in this frame grab made from a video recorded with a dashboard camera on a highway from Kostanai, Kazakhstan, to Russia's Chelyabinsk region Friday, February 15, 2013. (AP Photo/Nasha gazeta, www.ng.kz)

- **Enhance Earth Safety.** Enhance the safety of planet Earth by collaborating in the pursuit of planetary defense and orbital debris management mechanisms. Pursuing this goal lowers the risk of unforeseen future catastrophic asteroid collisions, as well as damage to current space assets in Earth orbit.
- **Extend Human Presence.** Explore a variety of destinations beyond low-Earth orbit with a focus on continually increasing the number of individuals that can be supported at these destinations, the duration of time that individuals can remain there, and the level of self-sufficiency. Extending and sustaining human presence beyond low-Earth orbit enables humankind to live and work in space, to harness solar system resources for use in space and on Earth, and eventually to settle on other planets. Pursuing this goal expands the frontiers of humanity, opens doors to future utilization of space, and reshapes how we think of ourselves and our place in the universe.

A Curiosity Mastcam photo showing a shale outcropping with crossbedding indicative of sediment transport in stream flows.

- **Perform Science to Enable Human Exploration.** Reduce the risks and increase the productivity of future missions in our solar system by characterizing the effect of the space environment on human health and exploration systems. This is essential for human exploration and will enable a human presence across the solar system. Pursuing this goal also yields innovation for Earth-based health care.
- **Perform Space, Earth, and Applied Science.** Engage in scientific investigations of solar system destinations, and conduct applied research in the unique environment at these destinations. Pursuing this goal delivers valuable knowledge to society and deepens understanding of our home planet.
- **Search for Life.** Determine if life is or was present outside of Earth and understand the environments that support it. The search for life is a central goal of space exploration. Pursuing this goal continues the cultural quest of humankind to determine whether we are alone in the universe, and answers deeply rooted questions about our origin and evolution. The question of whether life exists beyond Earth has great philosophical and scientific significance.
- **Stimulate Economic Expansion.** Support or encourage provision of technology, systems, hardware, and services from commercial entities and create new markets based on space activities that will return economic, technological, and quality-of-life benefits to all humankind. Pursuing this goal generates new industries, spurs innovation in fields such as robotics and energy systems, and creates high-technology employment opportunities. It allows the creation of commercial services and spinoffs to take place in a more effective and timely manner. As space activities evolve from government research to exploration to utilization, new economic possibilities may extend beyond low-Earth orbit to the Moon and elsewhere in the solar system.



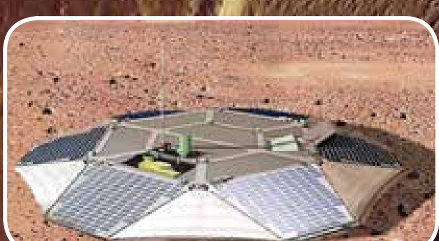
This mosaic is produced by combining multiple images of the Moon's south polar region. Regions in white are illuminated more often than grey regions. Many of the black areas are permanently shadowed and likely contain volatile deposits.

An exploration strategy will be based on goals and objectives that allow the sustainment and growth of each agency's aspirations for human space missions. As space agencies continue to refine their goals and objectives, they will share them and ensure that the Global Exploration Roadmap reflects the existing commonality.

Key Supporting Objectives

Goal	Objective
Develop Exploration Technologies and Capabilities	Test countermeasures and techniques to maintain crew health and performance, and radiation mitigation technologies and strategies.
	Demonstrate and test power generation and storage systems.
	Develop and test high-performance mobility, extravehicular activity, life support, and habitation capabilities.
	Demonstrate the use of robots to explore autonomously and to supplement astronauts' exploration activities.
	Develop and validate tools, technologies, and systems that extract, process, and utilize resources to enable exploration missions.
	Demonstrate launch and advanced in-space propulsion capabilities.
	Develop thermal management systems, including cryogenic fluid management capabilities.
	Learn how to best perform basic working tasks and develop protocols for operations.
	Test and demonstrate advanced entry, descent, and landing technologies.
	Test automated rendezvous and docking, on-orbit assembly, and satellite-servicing capabilities.
	Develop and demonstrate technologies to support scientific investigation.
	Develop space communications and navigation capabilities.
Engage the Public in Exploration	Use interactive communications tools to provide virtual experiences using real and live exploration data.
	Enlist amateur/citizen scientists to contribute to exploration-related knowledge collection.
Enhance Earth Safety	Characterize potential near-Earth asteroid collision threats.
	Test techniques to mitigate the risk of asteroid collisions with Earth.
	Manage orbital debris around the Earth.
Extend Human Presence	Explore new destinations.
	Increase opportunities for astronauts from all partner countries to engage in exploration.
	Increase the self-sufficiency of humans in space.
Perform Science to Enable Human Exploration	Evaluate human health in the space environment and develop methods to mitigate health risks.
	Monitor and predict radiation in the space environment.
	Characterize the geology, topography, and conditions at destinations.
	Characterize available resources at destinations.
	Evaluate the impacts of the surface, near-surface, and atmospheric environment on exploration systems.
Perform Space, Earth, and Applied Science	Perform Earth observation, heliophysics, and astrophysics from space.
	Gather scientific knowledge of destinations.
	Gather scientific knowledge of solar system evolution.
	Perform applied research.
Search for Life	Find evidence of past or present life.
	Explore the past or present potential of solar system destinations to sustain life.
Stimulate Economic Expansion	Provide opportunities for the integration of commercial transportation elements into the exploration architecture.
	Provide opportunities for the integration of commercial surface and orbital elements into the exploration architecture.
	Evaluate potential for commercial goods and services at destinations, including markets for discovered resources.

Chapter 3.
A Long-Range Human Exploration Strategy



Space agencies participating in ISECG have defined a long-range human exploration strategy that begins with the ISS and expands human presence into the solar system, leading to human missions to explore the surface of Mars. Unquestionably, sending humans to Mars in a sustainable way over time will be the most challenging and rewarding objective of human space exploration in the foreseeable future. These missions will require new technologies and significant advances in the capabilities we have today.

To enable a sustainable programme of human exploration of Mars, it is necessary to have a stepwise approach that reduces risk, tests advanced technologies and demonstrates new human space exploration capabilities. It is important that each mission can be defined in a way that takes a step toward Mars, while maximizing the opportunity to meet exploration objectives such as science, technology demonstration and public engagement.

From Strategy to Roadmap: Conceptual Mission Scenario

The ISECG Mission Scenario reflects the near-term initiatives in implementing the common strategy, namely: 1) fully utilizing the ISS, 2) continuing efforts to expand on synergies between human and robotic missions, and 3) discovery-driven missions in the lunar vicinity that evolve capabilities and techniques needed for Mars, while enabling discoveries on the Moon and near-Earth asteroids. This scenario reflects a coordinated international effort to advance common goals and objectives while enabling interested agencies to pursue their priorities and prepare for critical contributions to human Mars missions.

The scenario reflects a stepwise development and demonstration of capabilities necessary for executing increasingly complex missions, while focusing on discoveries at multiple destinations. Activities in the lunar vicinity and on the lunar surface can enable a variety of objectives related to asteroid and lunar exploration and significantly advance readiness for human exploration of Mars. Ongoing and planned robotic and human missions are critical for preparing for human missions to Mars.

Several driving principles (listed below) reflect the characteristics of a sustainable human exploration effort. The principles are highly interdependent, and it is the combination of these principles, rather than any individual one, that drives the development of sustainable mission scenarios. For example, affordability constraints at global levels dictate a stepwise approach to the development of new capabilities and a careful assessment of the need and timing for achieving redundancy for critical exploration functions. Affordability is also a function of the anticipated exploration value, as budgets may be subject to increase or decrease depending upon achieved exploration goals. Defining an affordable sequence for evolving capabilities that builds on competencies existing globally, enables a truly international space exploration effort.

Principles Driving the Mission Scenario:

Affordability – Take into account budget constraints

Affordability of a complex exploration programme must be maintained over extended periods of time. Cost must be a consideration when formulating programmes and throughout programme execution. Innovations and integration of advanced technologies must be driven by the goal to reduce costs. Each agency's planned contributions must accommodate realistic expectations regarding cost and the future availability of funding.

Exploration Value – Generate public benefits and meet exploration objectives

Sustainable human space exploration must respond to exploration goals and objectives and deliver value to the public as well as to participating stakeholder communities, beginning early in the process and continuing throughout the journey.

International Partnerships – Provide early and sustained opportunities for diverse partners

Broad international cooperation is not only critical for enabling increasingly complex exploration missions, but also an important contributor to achieving exploration value. Mission scenarios must build on the competencies and long-term interests of each agency, large or small, allowing each to sustain and grow its aspirations for space exploration. Collaborations will be established at all levels (missions, capabilities, technologies), with various levels of interdependency among the partners. These collaborations should be set up to ensure resiliency of the programme against failures, delays or programmatic issues. In addition, opportunities for new partners should be available to strengthen robustness of the overall partnership.

Capability Evolution – Execute missions of increasing complexity based on the stepwise development of capabilities

Sustainable human exploration beyond low-Earth orbit, toward the long-term goal of human missions to Mars, requires building upon existing capabilities and competencies, increasing performance with each step. New technologies should be pursued and applied to address challenges. Exploration mission challenges necessitate advancing and demonstrating critical capabilities to manage risk.

Human/Robotic Partnership – Maximize synergy between human and robotic missions

Combine the unique and complementary capabilities of humans and robotic systems, enabling a greater set of goals to be met effectively, cost-efficiently and safely. Robotic precursor missions will prepare for human missions by acquiring strategic knowledge about future destinations and demonstrating critical technologies. Use of robots to assist and complement crew activities will also enhance the productivity and benefits of eventual human exploration missions to any given destination.

Robustness – Provide for resilience to programmatic and technical challenges

A robust human space exploration programme will have sufficient flexibility to cope with unplanned changes or crisis situations, whether they are due to catastrophic events, changes in the partnership structure, adjustments in available funding or evolution of the exploration goals and objectives. To achieve robustness, dissimilar redundancies of critical functions should be applied early, where practicable.

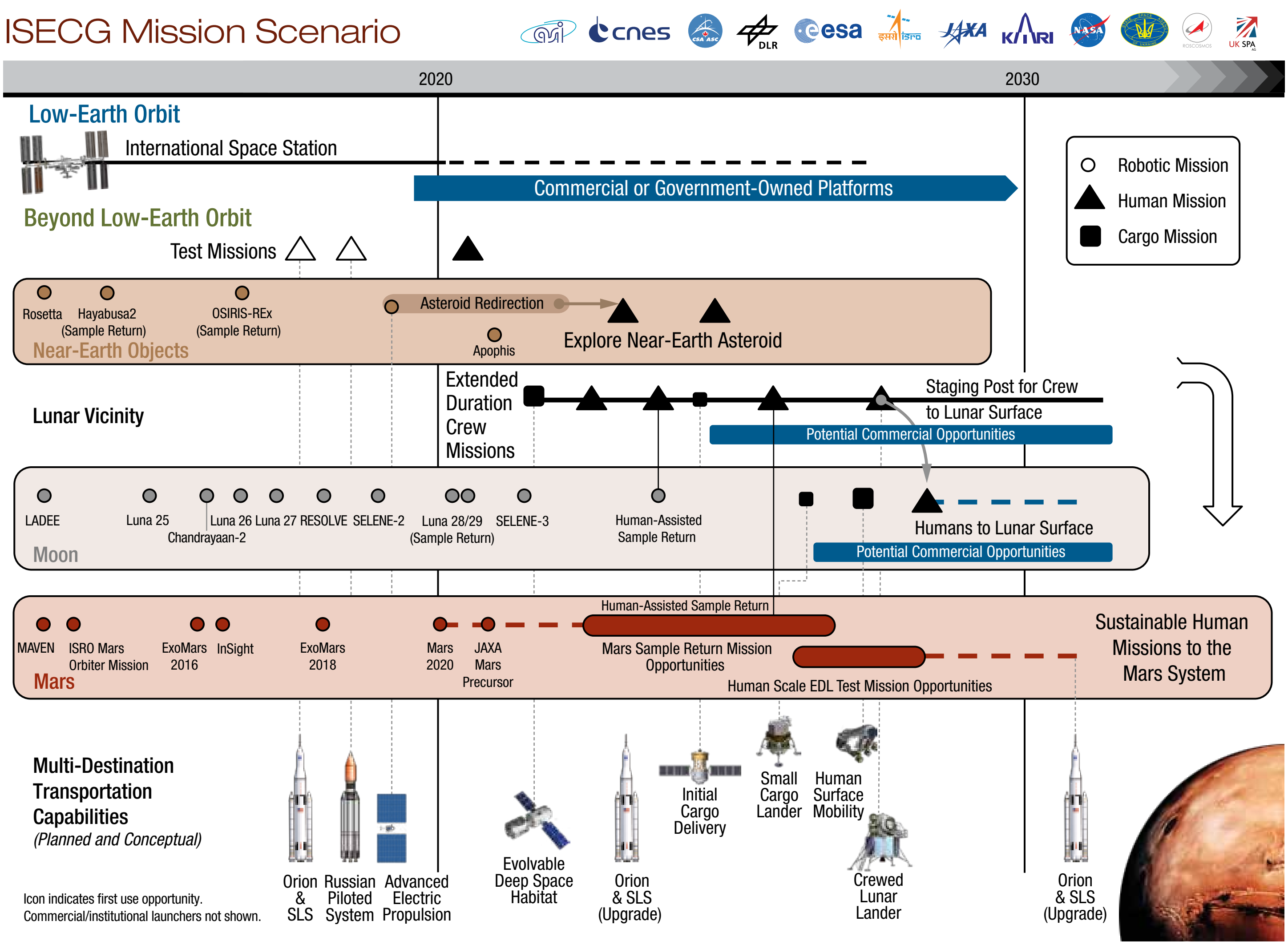
ISECG Mission Scenario

The ISECG conceptual mission scenario reflects missions in the next 25 years which significantly advance exploration objectives on the path to Mars. Missions in the lunar vicinity, such as those to an easily accessible asteroid or an evolvable Deep Space Habitat, can enable discoveries and allow demonstration of the systems on which long-duration missions into deep space must rely. Human missions to the lunar surface can allow demonstrations of planetary exploration capabilities and techniques, while pursuing the highest priority lunar science objectives.

As an evolution of the international coordination, the scenario reflects an integrated approach to human and robotic exploration. Crew presence brings human decision making, adaptability, and resourcefulness, enabling a larger set of science and exploration objectives to be met. Human-assisted sample return and tele-presence represent new and integrated approaches to space exploration with the potential to increase benefits. Mars sample return, a priority for the planetary science community, could bring insights which aid the preparation for eventual human surface missions. Human and robotic mission planners have begun a discussion on whether human presence could enhance sample return, while advancing other human space exploration objectives.

Human missions to the surface of Mars will require advances in entry, descent and landing capabilities. A human-scale Mars landing test is envisioned, providing an opportunity to also meet other science and precursor mission objectives.

The increasing role of private initiatives in low-Earth orbit opens the possibility that similar initiatives may be extensible to missions beyond.



Major Capabilities of Future Exploration Architectures

By examining various pathways to Mars, agencies have continued to study capabilities which enable human exploration of multiple destinations beyond low-Earth orbit. Sustainable missions to Mars will be possible if multiple agencies contribute critical capabilities. Agencies seek to make contributions which are consistent with their expertise and national objectives. Exploration capabilities will build on those developed in support of the ISS and other governmental or commercial space endeavours.

Exploration transportation capabilities under development today will enable missions in the lunar vicinity and are designed to be evolvable to support additional missions, such as lunar surface and deep space missions. Other capabilities, such as habitation, surface power, servicing and mobility will be needed over the long term and can be advanced in a stepwise manner to support exploration mission needs.

Icon	Capability Name	Description
	NASA Orion	Crew vehicle capable of delivering a crew to exploration destinations and back to Earth.
	NASA Space Launch System (SLS)	Launch vehicle with the capability to deliver cargo or crew beyond low-Earth orbit. Initial capability evolves with advanced boosters and an upper stage to enable increasingly complex missions with further evolution to support crewed Mars missions.
	Cryogenic Propulsion Stage (CPS)	Included in SLS evolution plans, an in-space propulsion capability utilizing cryogenic hydrogen and oxygen as propellants. Could provide additional performance for missions to the lunar vicinity, lunar surface or Mars. Mission durations will require long-duration storage of cryogenic propellants.
	ROSCOSMOS Next Generation Space Launch Vehicle	Launch vehicle with the capability to deliver cargo or crew beyond low-Earth orbit. The next generation space launch vehicle and the next generation spacecraft together constitute the Russian Piloted System.
	ROSCOSMOS Next Generation Spacecraft	Crew vehicle capable of delivering a crew to exploration destinations and back to Earth.
	Evolvable Deep Space Habitat	A human-tended habitat which is evolvable to advance in-space habitation, spacewalk, and staging capabilities ultimately required for human Mars missions.
	Servicing Support Systems	Systems and tools to enable crew and robots to service space systems and assemble larger capabilities. These systems can augment the functionality of the Orion and/or the evolvable Deep Space Habitat.
	Cargo Logistics Delivery Systems	Systems designed to serve as logistic vehicles for resupplying orbital infrastructures in lunar vicinity with pressurized and unpressurized payloads.
	Small Cargo Lander	System designed to deliver robotics and cargo on the lunar surface to meet lunar exploration objectives.
	Crewed Lunar Lander	Human-rated lunar lander that may have attributes of reusability, may be composed of two or more stages, and delivers crew and cargo to the lunar surface.
	Lunar Surface Elements	These systems have the capabilities that enable humans to effectively complete surface destination objectives, including human surface mobility, habitation and support elements.
	Advanced In-Space Propulsion	In-space stage using nontraditional propulsion technologies, such as high power electric and nuclear propulsion, to enable deep-space crew exploration of an asteroid and Mars.

Mission Themes

The ISECG Mission Scenario includes three different mission themes. Each theme includes a group of missions which may be accomplished with planned and conceptual capabilities. While each of these mission themes has its own rationale and is driven by individual objectives, each is considered a meaningful step toward the international partner-provided capabilities necessary for deep space and Mars missions. These themes also maximize the opportunity provided by the presence of the crew to address science priorities and engage the public in innovative ways.

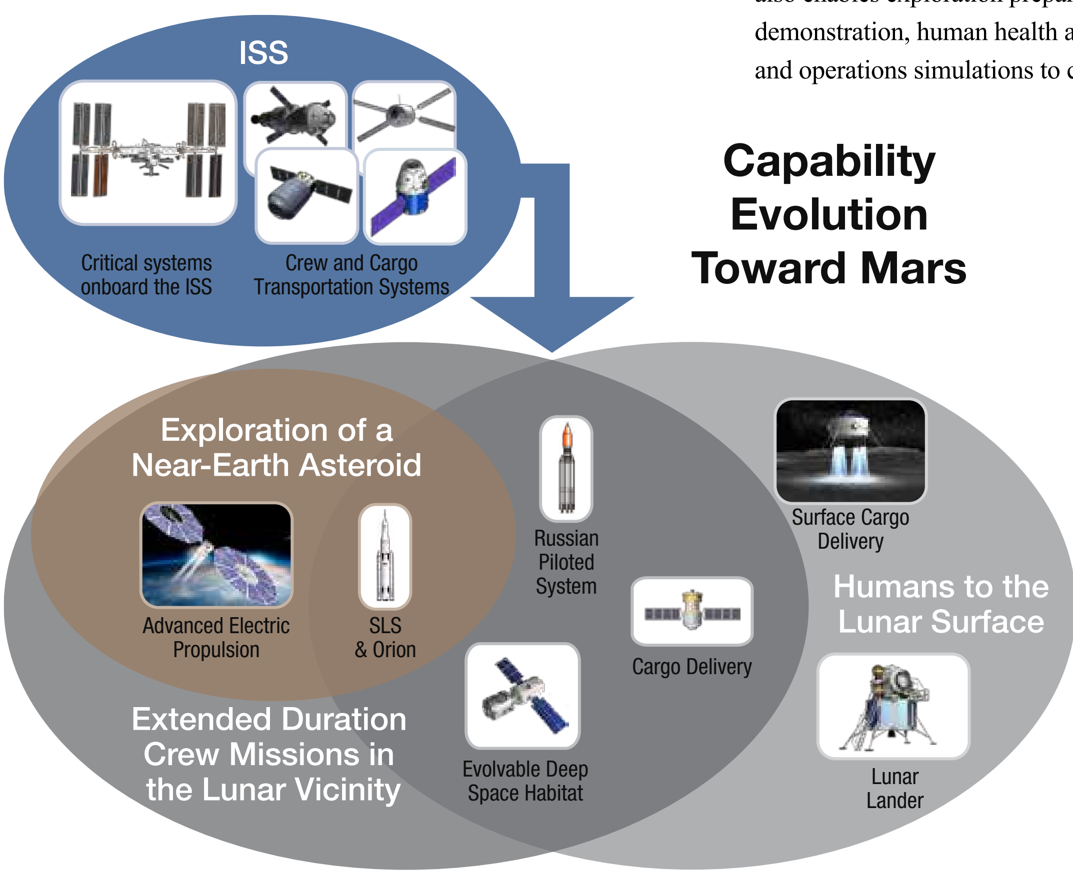
The three themes are as follows:

1. **Exploration of a Near-Earth Asteroid** – robotically deflecting an asteroid to enable its exploration in the lunar vicinity to demonstrate advanced electric propulsion, crew transportation and operation capabilities. This mission theme responds to a NASA initiative and includes opportunities for partnership.

2. **Extended Duration Crew Missions** – long-duration missions in the lunar vicinity for advancing deep space exploration capabilities and creating innovative opportunities for exploration of the Moon through a human-robotic partnership. This mission theme represents an achievable near-term step and has been defined with the goal to directly advance capabilities for future exploration missions targeting the Moon and deep space. This mission definition has been advanced collectively by ISECG agencies' representatives.

3. **Humans to the Lunar Surface** – missions to the lunar surface providing opportunities to address priority lunar exploration objectives benefiting from human presence on the surface and advancing habitation, mobility and other planetary exploration capabilities. This mission theme addresses one of the exploration destinations. Many agencies consider human missions to the lunar surface as an essential step in preparation for human Mars missions. Lunar missions are favored by agencies who view the Moon as the next step for human planetary exploration and NASA may contribute to such missions. Lunar missions have been studied individually and collectively, for several years.

It is important to enable beyond-low-Earth orbit missions while still operating and utilizing the ISS. Avoiding a gap between ISS and beyond-low-Earth orbit missions preserves the capabilities and expertise needed, as well as leveraging the ISS partnership for implementing future missions. Continued access to the ISS also enables exploration preparation activities, such as technology demonstration, human health and performance risk mitigation, and operations simulations to continue.



This figure illustrates how the systems and capabilities currently supporting the ISS form the basis for those needed to take humans farther into space. The habitation and other critical systems supporting astronauts on board the ISS will be evolved to meet exploration mission requirements. The crew and cargo transportation capabilities supporting the ISS provide a strong foundation for realizing similar capabilities needed for missions in the lunar vicinity. The stepwise evolution of current capabilities to those needed to execute missions in the lunar vicinity and the lunar surface will enable the international partnership to master the capabilities necessary to go farther into space.

Exploration of a Near-Earth Asteroid

This mission concept calls for a robotic mission to capture and redirect a small near-Earth asteroid and guide it to a stable orbit in the lunar vicinity, so that it is within reach of the Orion with the initial SLS performance. An asteroid of less than 10 meters in diameter would be targeted. An object of this size does not pose a threat to Earth. Once the redirected asteroid has achieved a stable orbit, astronauts (and robotic spacecraft) can visit and explore the object. Recognizing the variability of potential targets, other mission concepts are under study with the goal of maximizing the benefit for exploration and other in-space applications of technologies demonstrated on the mission.

Mission Activities

The robotic mission to redirect the asteroid will travel to the target object and employ rendezvous and capture techniques that may be suitable for other missions to non-cooperative targets, such as potentially hazardous asteroids or large uncontrollable space debris. Once the asteroid is delivered to a stable lunar orbit, astronauts in the Orion can visit and explore. Docking, grappling, or a similar approach would enable the crew to remain in the vicinity of the asteroid and accomplish planned tasks. Astronauts could perform spacewalks to enable closer examination of the asteroid, taking measurements and gathering samples for return to Earth. Mission activities could include:

- Characterize the composition of the asteroid
- Identify any resources and assess their potential for extraction
- Apply human evaluation capabilities to select samples for return to Earth laboratories, demonstrating sample acquisition, caching, storage operations, and crew transfer operations for future human-assisted sample return missions

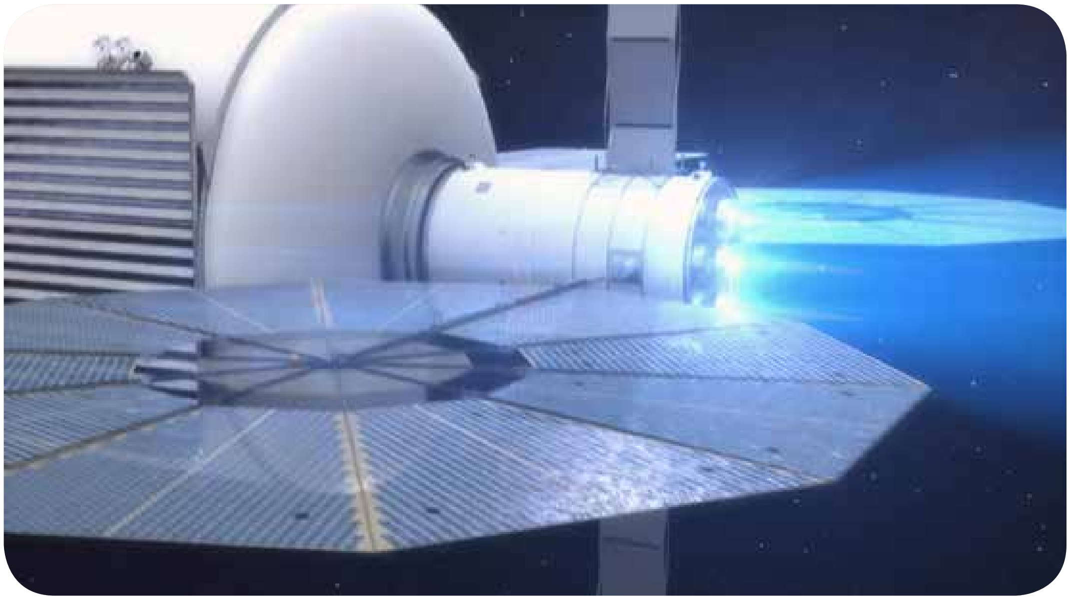
More than 10,000 near-Earth asteroids have been discovered. Several are considered to be possible targets for a mission of this nature, and global efforts to identify and characterize these objects are expanding. Characterization of potential targets contributes information towards understanding of the object's orbit, mass, spin rate and type. Each of these variables will affect mission and flight design. Ground-based and potentially space-based assets will be used to determine these characteristics of possible targets and are expected to be able to reduce their uncertainties to the point that a target can be determined to fall within the required range with reasonable confidence.

This conceptual mission advances high-power solar electric propulsion technologies that are essential for the safe and affordable exploration of Mars. This mission demonstrates large solar array structures and higher power electric propulsion systems. It provides the opportunity to integrate solar electric power systems into human exploration architectures, as human exploration of the asteroid will take place utilizing the integrated stack consisting of the Orion vehicle and robotic spacecraft.

Contributions to Mars Mission Readiness

Near-Earth asteroid missions could demonstrate the following core capabilities:

- Space Launch System, Orion
- 30-50 kW Solar Electric Propulsion System
- Spacewalk, rendezvous, proximity operations, docking or grapple, deep space navigation and communications



Very large solar arrays with roughly twice the power generating potential of today's state-of-the-art will be needed to power the proposed solar electric propulsion system.

Extended Duration Crew Missions

Advancing habitation capabilities beyond those currently in use on the International Space Station will be necessary to enable future deep space missions. This set of conceptual missions relies on the delivery of an evolvable Deep Space Habitat in the lunar vicinity that can accommodate life support and other habitation systems to demonstrate their use in an integrated fashion beyond low-Earth orbit. Several extended duration missions to the human-tended habitat are envisioned. Crew presence in the lunar vicinity will provide innovative opportunities for lunar exploration through applying human-robotic partnership concepts as outlined on page 22.

Mission Activities

A notional series of crewed missions using both the Russian piloted system and the NASA Orion have been defined. Key mission activities include:

- Advancing deep space human space flight operations and techniques, including staging operations
- Conducting high priority science benefiting from human presence, including human-assisted lunar sample return
- Testing technologies and subsystems benefitting from the deep space environment
- Characterizing human health and performance in a deep space environment

A single launch of the SLS could deliver the evolvable Deep Space Habitat to Earth Moon Lagrange Point 2. Using advanced solar electric propulsion, the habitat could be relocated to other locations in the lunar vicinity to meet science or exploration objectives. The initial configuration of the evolvable Deep Space Habitat will be driven by early mission objectives and SLS performance. Functionality can be added to the habitat as mission requirements dictate, to include such things as specific science equipment, servicing systems, additional docking ports, or fully closed-loop life support system elements. The crew would visit the habitat for stays of up to 90 days. Ninety-day stays have been chosen as an initial goal in order to test life support systems, perform crew health maintenance studies and drive reductions in the supply chain. Actual mission durations will be determined based on specific mission objectives, while balancing the benefits gained from longer crew stays against the cost of additional resupply missions.

In preparation for surface access missions, functionality could be added to the evolvable Deep Space Habitat so it may also serve as a staging post. Using a staging post to access the lunar surface facilitates integration of international and commercially available transportation assets as well as innovative lander concepts (such as a re-usable lander). This approach also offers the opportunity to simulate certain aspects of Mars surface access missions. In this way, it prepares partners interested in playing a critical role on human Mars missions to advance their capabilities and techniques as well as demonstrate architectural concepts directly relevant for human Mars missions while exploring the Moon.

Contributions to Mars Mission Readiness

Extended duration missions in the deep space environment could:

- Demonstrate deep space exploration capabilities such as SLS, Orion, advanced Russian crew transportation capabilities and life support systems, achieving an acceptable level of risk prior to travel to destinations away from the relative safety of Earth's orbit
- Demonstrate autonomous crew operation capability
- Demonstrate operations with reduced supply chain
- Increase experience with complex deep space staging operations
- Advance core technologies and radiation protection strategies for long duration missions
- Demonstrate interactive human and robotic operations analogous to Mars operational concepts
- Gain experience with solar electric propulsion used on a crewed spacecraft

Artist's concept of an evolvable Deep Space Habitat.

Human Lunar Surface Missions

This theme introduces conceptual human lunar surface access missions from the evolvable Deep Space Habitat. The optimum location of the staging post has not been determined at this time. Staging could be done from low lunar orbit, high lunar orbit or a Lagrange point, with each bringing unique advantages and constraints. Driven by the fulfillment of key lunar science and Mars preparation objectives, the mission scenario defines a lunar campaign with an 'exit strategy' consistent with moving forward with Mars mission readiness. However, participating agencies recognize that the fundamental capabilities are available to support additional missions in the event that lunar science or other exploration activities are identified.

Mission Activities

The major activities of human missions to the lunar surface would include:

- Test advanced surface power technologies
- Address high priority objectives of the science community which benefit from human surface presence
- Characterize human health and performance in a partial gravity environment
- Demonstrate long distance mobility concepts
- Explore concepts for human-robotic partnership in planetary surface exploration
- Utilize precision landing technologies demonstrated on robotic missions
- Advance knowledge base related to use of lunar resources
- Explore landing sites of interest for extended durations

Recent data from robotic missions, such as high resolution images, chemical composition data, and new analyses of Apollo samples (and lunar meteorites) using modern analysis techniques show that the Moon can tell us a lot about the formation of the solar system, and how it has evolved over time. This work has strengthened the scientific rationale for lunar exploration, which would benefit from returning humans to the lunar surface.

This mission scenario envisions a series of mobility-based extended-stay missions of increasing duration for up to one month in length. A crew would be delivered on a yearly basis to landing sites of interest and would explore the terrain in detail. As assets that enable longer stays are delivered to the surface, the ability to accomplish mission objectives will correspondingly increase substantially. Mars mission simulations would also be possible by delivering crew to the lunar surface after a lengthy stay on the evolvable Deep Space Habitat.

This mission scenario does not rely on the availability of lunar resources. Findings from robotic prospecting and extraction demonstration missions will inform future decisions regarding the promise of using lunar resources and may modify lunar surface or other human exploration approaches.

With a large number of planned lunar robotic missions in the next decade, it is considered likely that logistic services to the lunar surface will become commercially available, so they are included on the mission scenario.

Contributions to Mars Mission Readiness

Human missions to the lunar surface could:

- Demonstrate staging operations with an Earth-return vehicle
- Demonstrate extended crew mobility and habitation systems
- Demonstrate advanced power systems
- Characterize human health and performance, combining deep space and partial gravity environment exposure
- Demonstrate operations concepts and enhanced crew autonomy for surface exploration
- Potentially provide the opportunity for advancing concepts related to use of local resources

The human-rated Moon lander (European concept) on the lunar surface.

Human Mars Mission Risk Reduction

The ISECG Mission Scenario reflects a dedicated effort to define initial steps beyond low-Earth orbit that make a significant contribution to preparing for future Mars missions while enabling discovery along the way. The Mars mission risk reduction table, shown below, identifies key areas where solutions are needed to reduce the risk of human missions to an acceptable level. They have been derived from Mars mission architecture studies done by participating agencies and external groups in the past. The table reflects an assessment of opportunities to demonstrate the maturity of a technology, capability or operation to enable a human mission to the Martian surface and the respective risk reduction. The level of maturity was divided into three broad categories:

- Full utilization in relevant environment – same level of maturity required for a Mars surface mission.
- Sufficient risk reduction in relevant environment – not identical to requirement for a Mars surface mission, but ample in reducing risk for the Mars surface mission.
- Initial feasibility validation/partial validation – capability, technology or operational approach may be mature, but not in a relevant environment or partial demonstration of a capability, technology or operation.

The table is intended to be a top level illustration of how the ISECG Mission Scenario can drive the incremental reduction of risk. Missions in the lunar vicinity provide both the environments and key elements to significantly reduce most Mars mission risks. For example, a series of extended duration crew missions would enable both transportation and habitation risks to be reduced. A crew mission to an asteroid increases confidence in crew transportation and spacewalk capabilities. Lunar surface missions address habitation, mobility and other risks which are unique to operations on planetary surfaces. Following the conclusion of the lunar surface campaign, sustainable missions into deep space and Mars would be possible. If an orbital or fly-by mission to Mars or its moons were desired, that mission could effectively retire all but the key atmospheric and surface risks. And while crew members are vital for many of the Mars risks, an uncrewed medium-to-large scale robotic mission to the Mars surface would be sufficient for the residual atmospheric and surface risks.

● (green) **Full utilization in relevant environment** ● **Sufficient risk reduction in relevant environment** ⊙ **Initial feasibility validation/partial validation**	Earth	ISS/Low-Earth Orbit	Lunar Vicinity (Earth-Moon Lagrange Point (EML), Moon Orbit)	Moon Surface	Mars Vicinity	Mars Surface (Robotic Mission)
Beyond Low-Earth Orbit Crew Transportation			●	●	● (green)	
Heavy Lift Launch			⊙	●	● (green)	
Reduced Supply Chain		⊙	●	●	● (green)	
Autonomous Crew Operations	⊙	⊙	●	●	● (green)	
Deep Space Staging Operations			● (green)		● (green)	
Mars Ascent	⊙			⊙		⊙
Space Radiation Protection/Shielding		⊙	●	●	● (green)	
Life Support & Habitation Systems		●	●	●	● (green)	
Entry, Descent, & Landing Systems	⊙			⊙		●
Surface Power and Energy Management	⊙			● (green)		● (green)
Surface Mobility	⊙			●		●
Human Robotic Integration	⊙	●	● (green)	● (green)	● (green)	● (green)
Mars In-Situ Resource Utilization	⊙			⊙		●
Long Duration Human Health	⊙	●	●	●	●	
Deep Space Operation Techniques	⊙	⊙	●		● (green)	

Note: This table assumes critical capabilities will be provided by multiple agencies.

Observation:

➔ With the goal of enabling several partners to contribute critical capabilities to future human missions, agencies note that near-term collaborative missions on the ISS, in the lunar vicinity, on the lunar surface, and robotic missions may be used to simulate and better inform preparations for future international missions to Mars.

Human-Robotic Partnership

The conceptual architecture represented in the ISECG Mission Scenario provides the opportunity to study ideas which further expand the human-robotic partnership. New mission concepts, defined below, merit further study.

Human-Assisted Sample Return

The concept of human-assisted sample return is based on the assumption that human missions in the lunar vicinity will take place for advancing broader exploration goals and taking the first steps toward enabling human missions to the Moon, deep space and Mars. The presence of a crew can enhance the value of samples to the exploration community in the following ways:

- Increased science return with a larger and more diverse set of samples
- Reduced complexity of robotic mission, transferring sample handling responsibilities to the crew
- Improved mission robustness and reliability due to having a human in the loop
- Better opportunities for public engagement due to astronaut involvement, enabling demonstration of the significance of lunar science to a broader community
- Broader opportunities for international cooperation

Human space flight capabilities related to sample acquisition and return should strive to minimize the hardware and complexity required on the robotic vehicles.

Tele-Presence

Tele-presence can be defined as tele-operation of a robotic asset on a planetary surface by a person who is relatively close to the planetary surface, perhaps orbiting in a spacecraft or positioned at a suitable Lagrange point. Tele-presence is a capability which could significantly enhance the ability of humans and robots to explore together, where the specific exploration tasks would benefit from this capability. These tasks could be characterized by:

- High-speed mobility
- Short mission durations
- Focused or dexterous tasks with short-time decision-making
- Reduced autonomy or redundancy on the surface asset
- Contingency modes/failure analysis through crew interaction

From the ISS, astronaut Chris Cassidy operated this high-fidelity planetary rover, located at Ames Research Center's analogue facility. The ISS is conducting demonstrations such as this to gather engineering data useful to advancing the concept of tele-presence.

Artist's concept of opportunities to apply tele-presence capabilities to surface telerobotic operation.

Observation:

➔ New mission concepts, such as human-assisted sample return and tele-presence should be further explored, increasing understanding of the important role of humans in space for achieving common goals.

Use of Local Resources

Maintaining human presence beyond low-Earth orbit would benefit significantly from use of local resources. Use of local resources would limit the cost and complexity of bringing all the needed supplies from Earth. The most promising uses for local resource utilization are in life support systems or as propellants. The technology and capabilities needed to do this cost effectively and safely have progressed from paper concepts to systems developed and tested at analogue sites, but more work is required.

Mars resource utilization has primarily focused on providing rocket propellant (oxygen and possibly fuel) for ascent from the Mars surface to orbit, by processing carbon dioxide collected from the Mars atmosphere. Orbiting science spacecraft as well as Mars landers and rovers have confirmed that water, found in varying concentrations, depths, and forms all across the Mars surface, may also hold promise for future use. For example, the Mars Reconnaissance Orbiter confirmed the finding of water ice on the floor of certain craters, and the Phoenix lander confirmed dirty ice just below the surface at high latitudes.

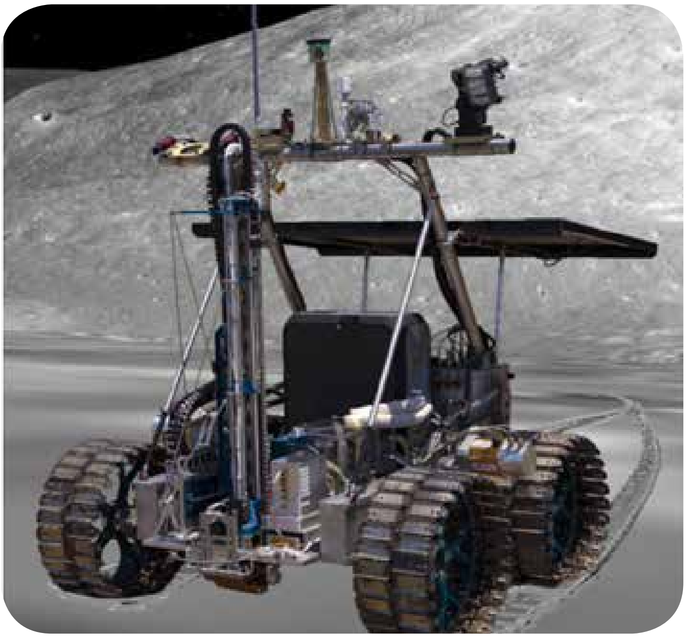
While the Moon does not have an atmosphere, the lunar regolith is known to contain oxygen. Techniques for its extraction have been proposed and demonstrated in the laboratory and in the field. In addition, the Lunar Reconnaissance Orbiter, Kaguya, Chandrayaan, and the Lunar Crater Observation and Sensing Satellite (LCROSS) have contributed information regarding the availability and distribution of volatiles at the lunar poles. Existing data indicate higher levels of hydrogen in the polar region, and the LCROSS spacecraft identified water and other volatiles at a single location in a permanently shadowed crater. However, neither the exact concentration of the volatiles in the regolith, nor the precise distribution (widely available near the surface or largely in permanently shadowed regions) are known.

To gain an understanding of whether lunar volatiles could be used in a cost effective and safe manner, it is necessary to understand more about the nature and distribution of the volatiles and whether they could be processed cost effectively. The first step is robotic prospecting to take measurements on the lunar surface. Several of the planned robotic missions can be considered prospecting missions. Additional information may be needed prior to committing to a processing demonstration mission, such as a mission with a rover capable of entering permanently shadowed regions of the lunar poles.

As much as 50 percent of near-Earth objects are thought to be potential resource targets, containing hydrated minerals and, in the case of dormant comets (e.g., P/Wilson-Harrington), subsurface reservoirs of water ice. Whether these volatiles can be used in a cost-effective manner is unclear. Because small bodies like asteroids and comets do not have significant gravity fields, the ISS may be a good location to demonstrate concepts for asteroid resource extraction and processing. A second step would be a small in-situ demonstration on a target remotely identified and characterized by ground-based and space-based telescope assets.

If these initial steps look promising, human missions to the Moon or an asteroid would provide valuable insight, assessment and troubleshooting for the robotic installation of a larger resource recovery and return facility.

While there are differences in the physical, mineral, and chemical forms of the soil on the Moon, asteroids, and on Mars, as well as different types and concentrations of ice and other volatiles, commonalities in technologies and processes can be found to reduce the cost and risk of using local resources. Planned robotic missions to the Moon and asteroids can provide information relevant to potential future Mars resource utilization by contributing information related to prospecting and processing techniques and equipment.



The RESOLVE payload concept shown prospecting for volatiles in a polar region of the Moon.

Standards to Promote Interoperability

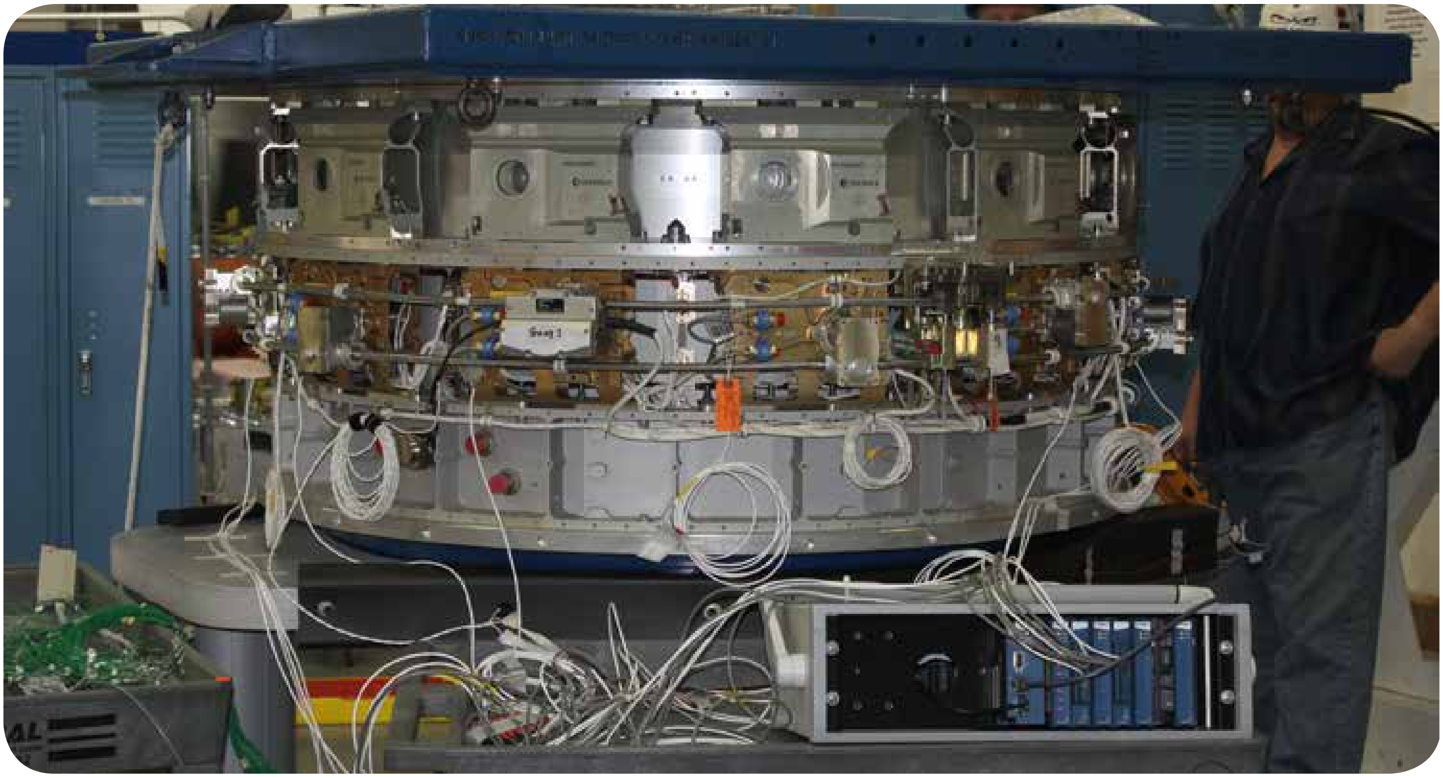
Partnerships among agencies in which each provides capabilities on the critical path to completion of mission objectives have become common, as mission complexity has increased and interagency relationships have strengthened. This is true for both human and robotic exploration initiatives. Large multinational exploration missions will require agencies to accept and manage interdependency at different levels: architecture, mission, infrastructure, and systems. The nature of human exploration beyond low-Earth orbit will necessitate acceptance of, and commitment to, a level of interdependency that is beyond our current experience and that will increase interoperability across the architecture.

Efforts to promote future interoperability of space systems are critically important. Pursuing interoperability initiatives, such as international standards and common interfaces, will ensure different systems and nations can work together in exploring the solar system. This is a proven approach to lowering the cost and risk of complex exploration missions.

Agencies participating in the Interagency Operations Advisory Group (IOAG), Space Frequency Coordination Group (SFCG), and the Consultative Committee for Space Data Systems (CCSDS) have collaborated on establishing data communications and mission operations architectures, coordinating spectrums for space communications, and technical standards for cross support which take advantage of current and anticipated state-of-the-art technologies.

Most of that work is already underway. These teams have developed service catalogs and technical standards which respond to the anticipated needs of future exploration missions. These services and standards will enable highly internetworked mission operations and facilitate the integration of new partners into complex human space exploration missions. More information about these international organizations is available at: www.ioag.org, www.sfcgonline.org, and www.ccsds.org.

In addition to the efforts in communications and operations, onboard systems standards are equally important. For example, initiatives such the International Docking System Standard and Onboard Data Interface Standards are essential for fostering onboard interoperability. Work on such standards continues. By applying them, vehicles developed by many nations can conduct missions such as those shown in the ISECG Mission Scenario and increase robustness in space exploration endeavours.



The NASA Docking System, shown here undergoing prototype testing, is compatible with the International Docking System Standard. Two ISS ports will be augmented with the system in 2015 to support visiting vehicles.

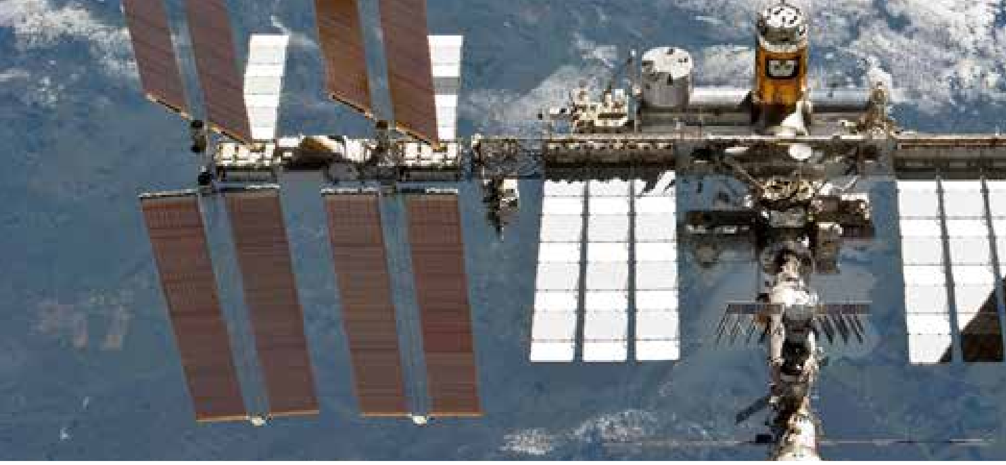
Chapter 4.
Human Exploration Preparatory Activities

Photo credit: AMASE/K.O. Storvik

Across the globe, engineers and scientists are working on many of the essential preparatory activities necessary to extend human presence into space and explore the planet Mars. By referring to a common roadmap, agencies are able to coordinate their preparatory activities in ways that maximize return on investments and enable realization of their goals and objectives.

Significant activities are underway in the following areas, each presenting opportunities for near-term coordination and cooperation, and each having direct and indirect benefit to people on Earth:

- Use of the ISS for exploration
- Robotic missions: An invaluable contribution to human exploration
- Advanced technologies
- A new generation of space systems and infrastructure
- Analogues to simulate exploration destinations
- Managing health and human performance risks for space exploration



Astronaut Kevin Ford works with InSPACE-3, investigating a new class of smart materials that may improve the safety and performance of mechanical systems in space and on Earth.

Use of the ISS for Exploration

With the decision to operate the ISS until at least 2020, ISS partner agencies continue to conduct a wide range of utilization activities on board the ISS, including life and physical sciences research, Earth and space observation, technology demonstrations, as well as many educational activities and initiatives. Fundamental and applied research activities in each of these areas contribute to overall scientific knowledge and generate significant benefits for humanity. In addition, ISS partner agencies are conducting activities which prepare for missions beyond low-Earth orbit.

Exploration missions will be at much greater distances from Earth, necessitate longer astronaut stays in space, and present new risks. The ISS is well suited to address these challenges. Exploration related activities on board the ISS can be grouped into four main areas of focus, as shown below.

Exploration Focus Areas

- **Exploration Technology Demonstrations**
  On-orbit demonstration or validation of advanced and promising technology that enables or improves exploration mission readiness.
- **Maturing Critical Systems**
  Driving evolution in capabilities supporting the ISS today, such as increased reliability, reduced mass and reduced power consumption.
- **Optimizing Human Health and Performance**
  Research to understand and reduce risks to human health and performance.
- **Operations Simulations**
  Furthering the understanding of the operations challenges associated with exploration missions.

Selected Recent Accomplishments

▶ The first phase of activities for the Robotics Refueling Mission experiment has successfully demonstrated how humans and robots working together can accomplish certain tasks which are fundamental to spacecraft repair, refueling and upgrade. New tests are planned for the coming years.

▶ The ISS cardiovascular equipment developed by CNES and partners (DLR for CARDIOLAB, ROSCOSMOS for CARDIOMED) is used to monitor key physiological parameters of the astronauts. The results are instrumental in preventing cardiovascular dysfunction in long-duration human exploration missions. In addition, CNES is expanding cardiovascular studies through investigations planned in the Chinese crewed module, TianGong.

▶ CSA's Microflow technology investigation tests a miniaturized flow cytometer in microgravity. Flow cytometry is used to focus blood and other body fluids into a controlled stream, enabling quantification of components and monitoring of physiological and cellular activity. The goal is a smaller and safer operational instrument for real-time medical care and monitoring during space flight.

Areas of Investigation

Crew Health and Performance

Human research on the ISS aims to devise and validate strategies to ensure optimal crew health and performance. Research is leading to a better understanding of risks and development of novel countermeasures against these risks. Countermeasures against cardiovascular, musculoskeletal, and neurological/behavioral challenges associated with space flight are critical for human space exploration. Nutritional countermeasures are also essential, given the impact of diet and nutrition on human health – in space and on Earth. Recent results have shown that having adequate vitamin D contributes to the bone health of returning astronauts. Other research has identified potential factors which might predispose individuals to certain vision changes during flight which could cause problems on future long-duration exploration missions.

One-Year Crew Mission

Four cosmonauts spent more than one year in space on board the Russian MIR space station. The longest mission, lasting 438 days, was conducted by Valery Polyakov from 1994–95. Since that time, significant advances in habitability systems and physiological response have been made. Countermeasures against the debilitating effects of microgravity on the human body have advanced considerably, with effective strategies for counteracting bone and muscle losses being employed. To look for relevant threshold effects in health and performance, the ISS partners have decided to extend the stay of two crew members beyond the current six-month stay to 12 months in 2015. This one-year mission will provide the opportunity to validate physical countermeasures applied to maintain bones, muscles and overall fitness, and use modern analysis techniques to identify any new areas of concern.

Crew Autonomy

Missions to Mars will require a degree of crew autonomy not seen in the operation and utilization of the ISS. Providing the crew with the training and tools to operate complex spacecraft without the constant supervision of ground control centers will be necessary due to long communication delays (up to 20 minutes each way for Mars missions). Studies on board the ISS have begun to reveal the considerations associated with delayed communication and increased crew autonomy.

Life Support

Work on the ESA Advanced Closed Loop Life Support System is an example of what is needed to reduce astronaut reliance on resupply of breathing gasses during long-duration missions.

Living in space for long durations with little or no resupply of water and oxygen is a fundamental capability that is being matured through day-to-day operations on the only platform capable of the task – the ISS. This is because the technologies dealing with gases and liquids are highly dependent on the gravity environment. The ISS Programme is using routine upgrades of the current life support systems to increase operational availability and reduce system mass, consumables, and power needs beyond the current technology.

Alternate prototype technologies for exploration missions, such as Amine Swingbed carbon dioxide removal, are also operating on the ISS. The Amine Swingbed technology is targeted for use on the Orion.

Space Power and Energy

Advanced ISS batteries.

Solar array demonstrations in space are important because they can be done in an environment without the filtering caused by the atmosphere, while also providing the appropriate thermal and dynamic loading conditions. Fuel cells and other systems that operate with fluids, especially two-phased fluids, benefit from testing in the microgravity environment.

New solar cell materials have already been demonstrated on the ISS, and solar array demonstrations are now being considered on ISS resupply vehicles. Advanced regenerative fuel cell technologies, whose operations depend on considerable fluid management, are also envisioned for demonstration on the ISS to determine the performance of the systems in microgravity.

Human-Robotic Partnership

Human robotic collaboration onboard the ISS.

Robotic and telerobotic systems operating in and around a crewed spacecraft, with or without crew-robot interaction, illustrate a concept of operations that enables the unique contribution of each to enhance mission objectives. Robonaut, the robot crew member, has started to execute routine ISS maintenance tasks which would normally take time away from the crew's ability to do research. Low-latency telerobotics demonstrations planned for the ISS will evaluate the benefits of using crew in orbit around a planetary surface to perform high-value exploration activities by controlling robots on the surface.

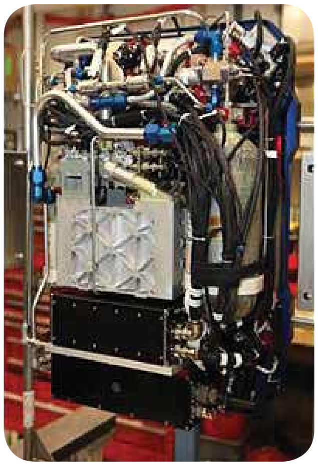
Advanced Communications and Navigation

The Space Communications and Navigation testbed installed on the ISS advances research on radio communications and the Global Positioning System.

Technologies associated with automated communication, navigation and docking/berthing have matured greatly with ISS resupply vehicles such as Progress, H-II Transfer Vehicle, Automated Transfer Vehicle and Dragon. The dynamics of deep space navigation and docking are completely different and will drive significant advances. Some of these advances can be tested on the ISS; others will require missions beyond low-Earth orbit to master. Several navigation systems are under evaluation for demonstration on the ISS. Disruption tolerance systems are already being demonstrated on the ISS, with increased utilization of the protocols planned.

New Space Suits

Extravehicular activity systems upgrades, stowage management, and environment (dust, background noise) demonstrations are already being performed on the ISS. Next generation space suit subsystems will be delivered to the ISS in the next several years.



Prototype Portable Life Support System to be flown aboard the ISS.

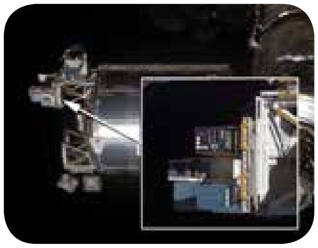
Entry and Descent Systems

Re-Entry Breakup Recorder (REBR)

Visiting vehicles re-enter Earth's atmosphere following missions to the ISS. There are also several methods to deploy small satellites from the ISS which will re-enter the atmosphere. These opportunities can be used to demonstrate capabilities and increase knowledge of atmosphere entry environments.

Several demonstrations have recorded data characterizing the environment in a vehicle breaking up in the atmosphere, providing insight into defining this environment. Ablative material that is being considered for future spacecraft is also being used on uncrewed vehicles returning from the ISS without risking a crew in the demonstration.

Materials, Structures and Manufacturing



The European Technology Exposure Facility mounted outside the Columbus module.

Long-duration exploration missions will experience the ultra violet, thermal and radiation environment of space, requiring the use of materials on spacecraft which can survive these harsh conditions. The ISS provides a long-duration platform where these materials can be evaluated. The first inflatable habitable module to be tested with humans in space will take place in 2015. The demonstration will assess the structural integrity and leak rate of this inflatable structure in the radiation and micrometeroid environment of the ISS.

ISS Partners continue their efforts to make the use of the ISS available to non-ISS partner nations. Researchers from 80 nations have taken advantage of the ISS to perform a variety of investigations. ISS partner agencies welcome proposals for using the ISS to advance readiness for future exploration missions.

Self-portrait of NASA's Mars rover Curiosity at John Klein rock in May 2013.

Robotic Missions: An Invaluable Contribution to Human Exploration

Since Project Apollo, robotic missions have served as the precursors to human exploration missions. Beginning with Ranger, Surveyor, and Lunar Orbiter, the data collected have defined the boundary conditions and provided information on the environment to inform the first human missions to the Moon. Agencies are planning a number of robotic missions to destinations reachable by humans. Almost all are done through international partnership. Most of these robotic missions are driven by scientific objectives; some have originated as human precursor missions. In each case, information is gathered which is useful for meeting science and human exploration goals. Increasingly, science missions in the formulation phase are creating opportunities to gather information and demonstrate technologies needed to prepare future human missions. To facilitate this effort, strategic knowledge gaps have been defined and discussed by participating agencies. These are summarized on page 31.

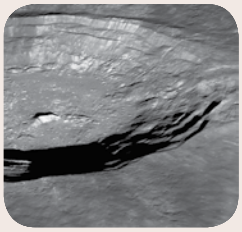
Robotic missions to human destinations that are planned by agencies contributing to the roadmap are shown on page 30.

Hayabusa2 Flight Model under development

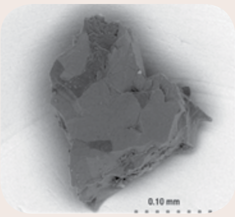
Observation:

➔ Robotic science missions provide an important technique for obtaining the data needed to prepare for human exploration beyond low-Earth orbit. It is generally accepted by both the science and exploration communities that measurements and data sets obtained from robotic missions support both the advancement of science and preparation for human exploration.

Selected Recent Accomplishments



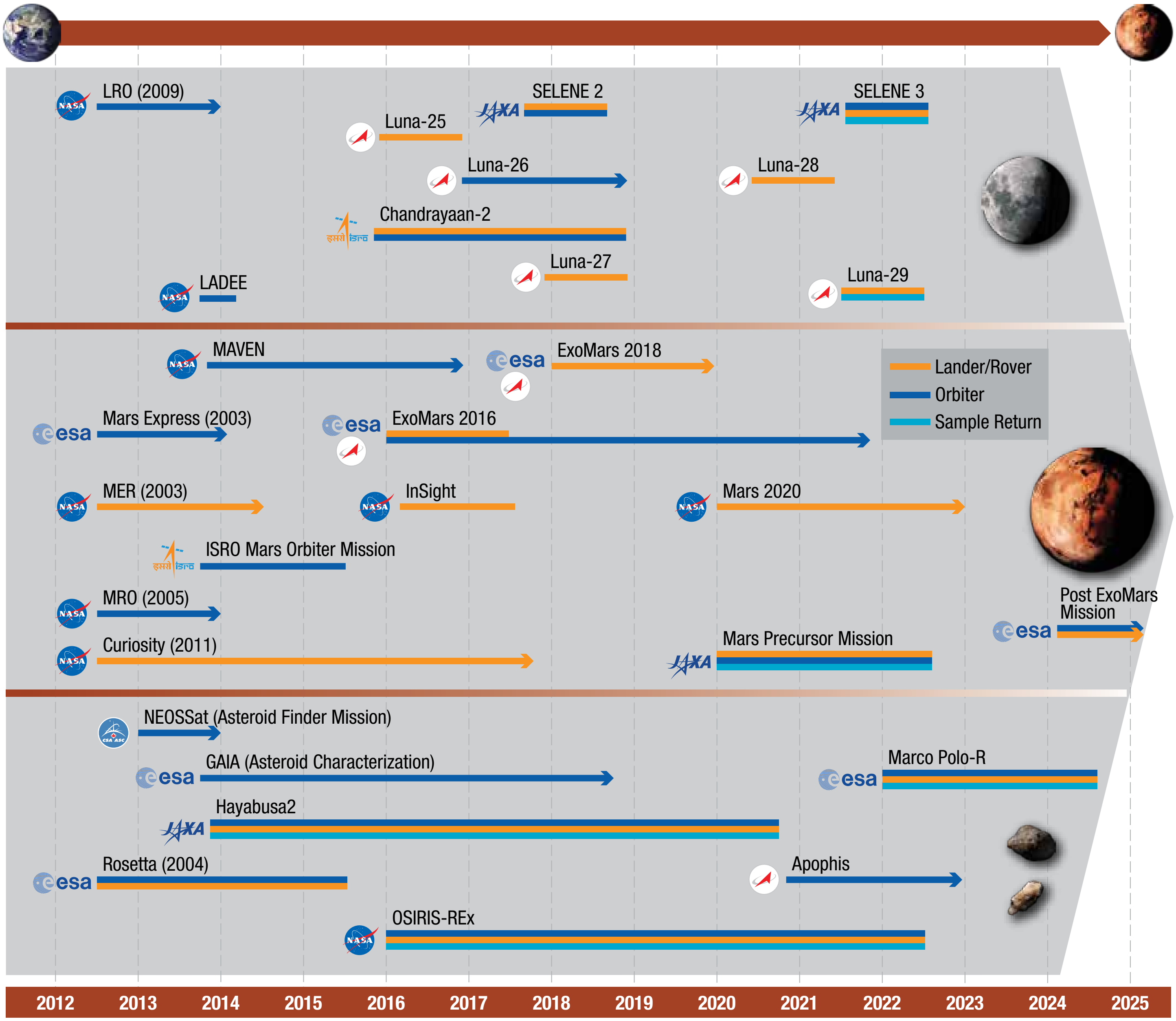
- Ongoing observations from NASA's Lunar Reconnaissance Orbiter have provided high resolution images, precision topography, thermal mapping, and other advanced remote sensing data that provide a dramatically more comprehensive understanding of the lunar environment, associated hazards to human space flight, and the location of potential resources.



- JAXA's Hayabusa explorer characterized asteroid Itokawa and enabled a comprehensive analysis of the first samples ever returned directly from an asteroid to Earth, providing quantitative links between the chemical analyses of meteorites found on Earth to spectroscopic measurements of asteroids.

- NASA's Curiosity captured data which characterized the Mars atmosphere during entry and descent and the first measurements of space radiation on the surface of Mars.

Planned Robotic Missions to Future Human Destinations



Most robotic missions are conducted with international participation of some nature. Forms of international cooperation include joint development of the spacecraft, provision of instrumentation, and others. The table to the right highlights some examples of international cooperation on robotic missions. The lead agency for developing the spacecraft is shown as well as the agencies providing contributions to scientific instrumentation.

Mission	Lead Agency	Agencies Providing Instruments
Curiosity	NASA	CNES, CSA, DLR, Roscosmos, Spain
ExoMars	ESA, Roscosmos	ASI, Belgian Space Agency, CNES, DLR, NASA, Spain, Swiss Space Office, and UK Space Agency
Hayabusa2	JAXA	CNES, DLR
InSight	NASA	CNES, DLR, UK Space Agency, Switzerland, and Spain
OSIRIS-REx	NASA	CSA

Strategic Knowledge Gaps: Definition and Assessment

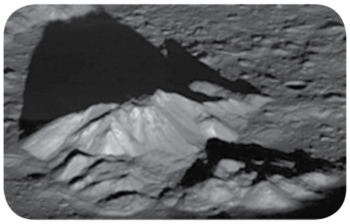
In order to prepare for future human missions, system and mission planners desire data that characterize the environments, identify hazards, and assess resources. Recent, currently operating, and future science missions are invaluable resources for providing this data. The knowledge developed from this data will inform the selection of future landing sites, inform the design of new systems, and reduce the risk associated with human exploration. While some data can be obtained through ground-based activities, other data can only be gained in space by remote sensing, in-situ measurements or sample return.

Recognizing that much of the information desired by human mission planners is of equal interest to the science community, ISECG participating agencies have worked with relevant groups to identify Strategic Knowledge Gaps (SKGs) associated with future human destinations. In consultation with key independent analysis/assessment groups from NASA, ESA Topical Teams, and JAXA experts, the list has been integrated and grouped by areas of knowledge for each destination.

The list of SKGs has been prioritized on the basis of crew/mission risks, relevance to mission scenario, and applicability to more than one destination.

The table below provides an example of SKGs for each potential destination, Moon, asteroid, and Mars. It provides insight into how the gaps are categorized and the information which is available on each gap. The list of SKGs has been summarized and the high-level SKGs list can be found on the ISECG Web site[1]. It contains information on the gaps and their priority. It also identifies specific measurements which would contribute to filling the gaps. Lastly, the list gives insights into how recent and planned robotic missions and ground-based activities will contribute information related to the gaps, and where additional measurements will be useful to fill the gaps.

Whether robotic mission formulation is primarily for scientific investigation or to prepare for human exploration, there are opportunities to significantly increase the benefit to each community. The SKG analysis will support the identification of the appropriate steps toward further coordination in order to increase the value of space exploration investments to our global stakeholder community. The SKG work is intended to inform the definition of objectives for future robotic missions and ground-based activities.

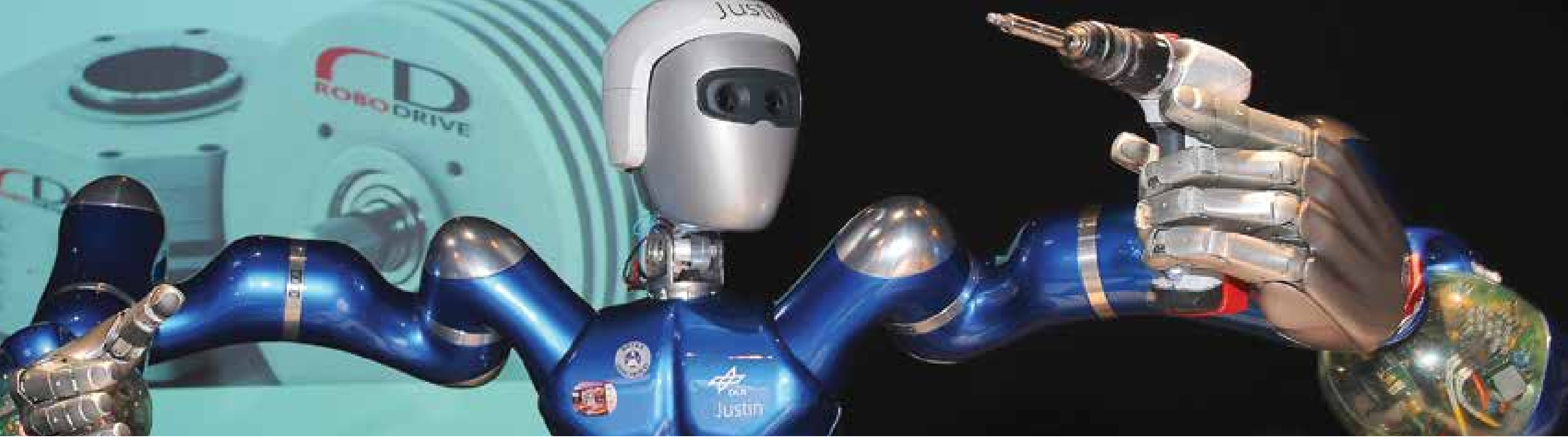


A sunrise view of Tycho crater's central peak captured by NASA's Lunar Reconnaissance Orbiter.

ISECG remembers Dr. Michael Wargo (NASA) who led the international effort to identify human exploration SKGs. His talents and enthusiasm for space exploration will be missed by many around the world.

Destination	Knowledge Domain	Strategic Knowledge Gap: Description and Priority	Target Measurement	Mission or Ground Based Activity Addressing the SKG	Additional Measurements: R = Robotic Mission SR = Sample Return G = Ground Based Activities
Moon	**Resource Potential**	**Lunar Cold Trap Volatiles:** Composition/quantity/distribution/form of water/H species and other volatiles associated with lunar cold traps.	In-situ measurement of volatile characteristics and distribution within permanently shadowed lunar craters or other sites identified using remote sensing data (e.g., from LRO)	Roscosmos Luna-25/ Luna-27/Luna-28 and 29 NASA-CSA RESOLVE	R, SR
Near-Earth Objects (NEO)	**Human Mission Target**	**NEO Composition/Physical Characteristics:** Rotation State	Light curve and radar observations from different ground (Earth based telescopes) and space based assets.	e.g.: Goldstone Observatory (US); Bisei Spaceguard Center (Japan), Observatoire du Pic du Midi (France)	G, R
Mars	**Atmosphere**	**Atmospheric Modeling:** The atmospheric models for Mars have not been well validated due to a lack of sufficient observational data, and thus confidence in them is limited.	Density, pressure, temperature, and wind data, trajectory performance information	NASA Viking, Pathfinder, MGS, MERs, Phoenix, MRO, MSL ESA Mars Express ESA-Roscosmos ExoMars 2016, 2018	G, R

[1] www.globalspaceexploration.org



DLR's humanoid robot, Justin, demonstrates dexterous tool handling.

Advanced Technologies

While space-faring nations have made major technology progress and surmounted great challenges over the last 50 years, additional technological advances are required to enable sustainable future exploration missions. To achieve this, a summary of the exploration technology development activities of participating agencies has been shared and discussed. Gaining a common understanding of the activities and priorities of other agencies can inform agency decision making in each individual investment area. By sharing information related to technology focus areas, opportunities for collaboration can be identified.

Sustainable missions to Mars, including exploration of intermediate destinations, will require certain technologies that have been identified as critical needs. These are summarized on page 33. By assessing ongoing technology development activities against critical needs, it is possible to identify development gaps, i.e., technologies where the current portfolio of activities from the participating agencies is unlikely to meet the required performance in the desired timeframe. These findings may provide opportunities for increasing collaboration between interested agencies.

The next generation of large Canadian Space Agency robotic manipulators will feature telescopic booms and will meet the tight packaging and launch constraints of future exploration vehicles, such as Orion.

Selected Recent Accomplishments

- The Robotic Exploration of Extreme Environments research alliance established in Germany in 2012 aims to share expertise between lunar robotic systems and terrestrial deep sea exploration to identify, develop and test technologies that will support operations in highly inaccessible terrain, either on Earth or other planets.

- JAXA is developing key technology for advanced cryogenic propulsion stages, including a high performance expander bleed cycle engine with re-ignition capability, efficient propellant utilization, and advanced tank insulation.

- NASA successfully conducted a suborbital flight test to demonstrate the feasibility of inflatable heat shields as a means to eventually land larger payloads on Mars. This technology could increase the capacity of landed missions for both science and human exploration missions.

Critical Technology Needs by Technology Area[2]

In-Space Propulsion Technologies (TA02)	Life Support & Habitation Systems (TA06)
• Liquid Oxygen/Methane Cryogenic Propulsion System (Mars Lander) • Advanced In-Space Cryogenic Propellant Storage & Liquid Acquisition • Electric Propulsion & Power Processing • Nuclear Thermal Propulsion (NTP) Engine	• Closed-Loop & High Reliability Life Support Systems • Fire Prevention, Detection & Suppression (reduced Pressure) • EVA Deep Space Suits, including lunar & Mars environment • Advanced EVA Mobility (Suit Port)
Space Power & Energy Storage (TA03)	**Long Duration Human Health (TA06)**
• High Strength & Autonomously Deployable In-Space Solar Arrays • Fission Power for Electric Propulsion & Surface Missions • Regenerative Fuel Cells • High Specific Energy & Long Life Batteries	• Space Flight Medical Care, Behavioral Health & Performance • Microgravity Biomedical Countermeasures • Human Factors & Habitability • Space Radiation Protection/Shielding
Robotics, Telerobotics & Autonomous Systems (TA04)	**Human Exploration Destination Systems (TA07)**
• Telerobotic control of robotic systems with time delay • Robotic Systems Working Side-by-Side with Suited Crew • Autonomous Vehicle, Crew, & Mission Ground Control Automation Systems • Automated/Autonomous Rendezvous & Docking & Target Relative Navigation	• Anchoring Techniques & EVA Tools for Micro-G Surface Operations (NEO) • Surface Mobility • Lunar & Mars ISRU In-Situ Resource Utilization • Dust Mitigation
	Entry, Descent, & Landing Systems (TA09)
	• Entry, Descent, & Landing (EDL)—Mars Exploration Class Missions • Precision Landing & Hazard Avoidance
Communication & Navigation (TA05)	**Thermal Management Systems (TA14)**
• High Data Rate Forward & Reverse Link Communications • High-rate, Adaptive, Internetworked Proximity Communications • In-Space Timing & Navigation for Autonomy	• Low Temperature Mechanisms (lunar poles) • Robust Ablative Heat Shield—Thermal Protection Systems (Mars & lunar re-entry velocities)

Many of the critical technology needs listed in the table above are being pursued by space agencies around the world. However, appropriately funding the areas of critical technology highlighted below would yield novel approaches to and significantly increased capabilities for exploration missions:

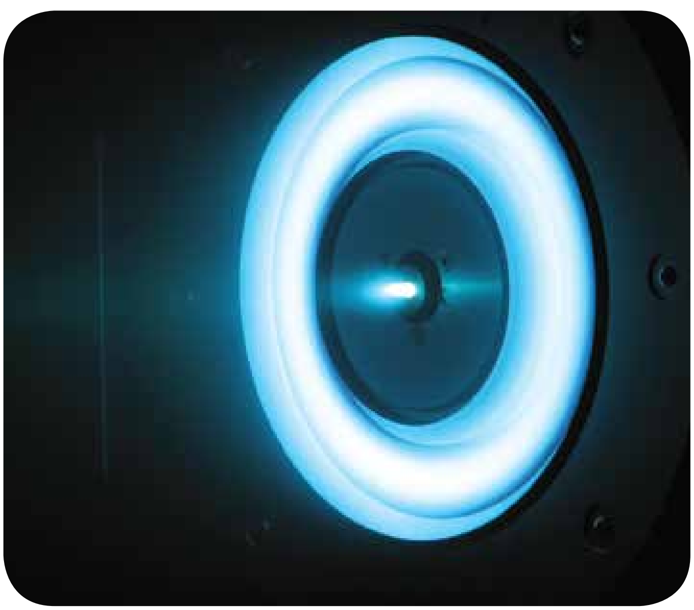
1. **Nuclear Power for Electric Propulsion and Planetary Surface Applications**
   Surface fission power systems on the order of 40 kWe, at 150 kg/kWe, would greatly enhance exploration and science activities on the Moon and Mars. A power system of these characteristics would also advance the state of electric propulsion vehicles. Very high power electric propulsion vehicles, on the order of >1 MWe with low mass (<15 kg/kWe), can more efficiently deliver cargo and crew to beyond-low-Earth orbit destinations.

2. **High Rate, Adaptive, Internetworked Proximity Communications**
   This ability enables high data rate (>20Mb between peers) communications between multiple in-space flight elements for situational awareness, and element proximity radios to sense radio frequency conditions and adapt autonomously. In addition, this capability enables elements to store, forward, and relay/route information to other elements intelligently and enables element radios to be reprogrammed from ground-based assets when communications are available.

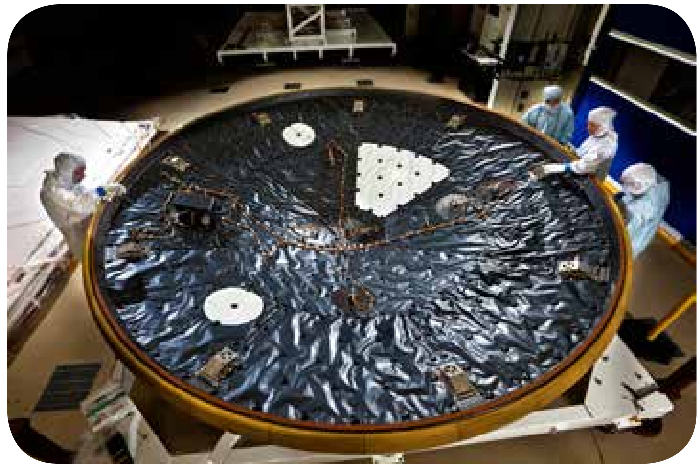
[2] The definitions of the technology areas can be found at www.nasa.gov.

3. **Low Temperature Mechanisms for Surface Missions**
Future deep space missions will demand safe and reliable mechanical systems over long durations and in extremely challenging environments, such as cryogenic temperatures and ultra-high vacuum. Long life, cryogenic actuators are a key technology challenge and needed for outer planet and deep space probe missions. Long-life-by-design, modular (for ease of integration) actuators consisting of motors, gearboxes, position/speed sensors, and motor controller electronics will need to be capable of operating in dusty asteroid or lunar environments at temperatures between 40K and 400K for years in order to meet those reliability demands.

Two rovers demonstrate reliable autonomous mobility software in an analogue environment (K-REX on the left, and Artemis Jr./Canadian Space Agency).



NASA is developing high-power electric propulsion systems to provide reliable operation for long-duration missions.



For the first time, instrumentation to measure pressure and temperature during Mars entry and descent was flown on the Curiosity mission. This knowledge will lead to improvements in future Mars heat shield design.

The same analysis also identified several areas for which a majority of participating agencies (i.e., six or more) have stated investment plans as follows:

- Automated/autonomous rendezvous and docking, proximity operations, and target relative navigation
- Telerobotic control of robotic systems with time delay
- Anchoring techniques and extravehicular activity tools for microgravity surface operations
- Long duration space flight medical care
- Long duration space flight behavioral health and performance
- Microgravity biomedical countermeasures for long duration space flight
- Space radiation protection
- In-flight environmental monitoring
- Surface mobility
- Thermal control

Although this preliminary analysis did not thoroughly and completely assess the ISECG community's technology portfolio, it has provided an ability to evaluate critical needs mapped to investment planning for the individual agencies. As with any high-level analysis, follow-up discussions with the specific agency technology developers will provide the level of detail needed for making informed decisions.

A New Generation of Space Systems and Infrastructure

Human exploration beyond low-Earth orbit will require a new generation of capabilities. These future systems will incorporate technologies still to be developed, and build not only upon existing capabilities and competencies, but also on the lessons learned and experience gained from them. New systems must be reliable and safe, because interplanetary resupply missions from Earth will not be able to reach the crew on short notice, and quick return to Earth will not be possible. Progress is being made in developing key transportation systems necessary to support human exploration.

NASA's Orion Spacecraft

Orion is NASA's space exploration crew vehicle, capable of taking humans on long-duration deep space missions and returning them to Earth. The first flight of Orion on the Space Launch System is scheduled in 2017. Orion consists of three modules, a launch abort system, a crew module and a service module.

The **Launch Abort System**, positioned on a tower atop the crew module, activates within milliseconds to propel the crew module to safety in the event of an emergency during launch or climb to orbit.

The **Crew Module** is the transportation capsule that provides a safe habitat for the crew, provides storage for consumables and research instruments, and serves as the docking port for crew transfers. The crew module is the only part of the Orion that returns to Earth after each mission.

The **Service Module** is the powerhouse that fuels and propels the Orion spacecraft, providing the capability for orbital transfer, attitude control, and high-altitude ascent aborts. Service Module systems also provide the water, oxygen and nitrogen needed for a habitable environment, generate and store electrical power, and maintain the temperature of the vehicle's

Selected Recent Accomplishments

- Hardware for NASA's Orion is being integrated in preparation for the first orbital test of the new spacecraft, planned for late 2014.

- NASA's Michoud Assembly Facility is being prepared for assembly of the core stage of the Space Launch System. The Vertical Weld Center will be used to create the large stage from barrel sections.

- NASA is developing launch site infrastructure to prepare, assemble, test, launch and recover the SLS and Orion flight systems at Kennedy Space Center

- ESA is advancing work on a development model of the International Berthing and Docking Mechanism (IBDM) designed in full coherence with the International Docking System Standards. It allows docking with reduced impact loads and therefore enables docking to a wide range of targets, including with low mass/inertia. Elements of the IBDM may be integrated into existing docking devices to enhance their versatility.

systems and components. The Service Module is mated to the Crew Module throughout the mission, until just prior to re-entering Earth's atmosphere. The European Space Agency will provide the service module for Orion's uncrewed Exploration Mission 1, scheduled for 2017.

All of the spacecraft subsystems and components built across the country are coming together at the Kennedy Space Center. They will be integrated into NASA's Orion spacecraft for the Exploration Flight Test 1 in 2014. Data gathered from the flight test will influence design decisions, validate existing computer models, drive innovative new approaches to space systems development, and reduce overall mission risks and costs for later Orion flights.

NASA's Space Launch System

The Space Launch System is the heavy-lift launch vehicle that will enable future exploration missions. As a human-rated launcher, it can carry the Orion and its crew to destinations beyond low-Earth orbit. It is evolvable and could be used to launch habitats, transfer stages, landers, robotic spacecraft and other capabilities needed for future missions. In support of robotic precursor missions and science missions, the Space Launch System could provide the volume needed to allow simpler designs and the velocity required to send spacecraft to their destinations with shorter transit times.

In 2017, the Space Launch System's initial 70 ton configuration will make its first flight – an uncrewed test of the Orion spacecraft. In 2021, it will transport the Orion and its crew to trans-lunar injection. The 70 ton rocket is comprised of a liquid hydrogen/oxygen core stage with four engines, two five-segment solid rocket boosters, and an interim cryogenic upper stage.

The Space Launch System will evolve from a 70 ton lift capability to the 130 ton configuration. While focused on delivering the initial capability for a 2017 launch date, work has already begun to evolve the rocket. For example, hardware risk-reduction is taking place for both liquid and solid advanced boosters. In addition, NASA is studying options for advanced cryogenic upper stages to enable additional missions as the system evolves into the most capable launch vehicle ever flown.

Roscosmos' Transportation System

A new Russian piloted space transportation system is under development. The new system will build on the extensive accomplishments of the Soyuz vehicle and be capable of taking astronauts to the vicinity of the Moon and return them to Earth. It is comprised of a next generation crew transportation system and a next generation space launch vehicle. The first flight of the new crew transportation vehicle is envisioned for the 2018 timeframe. The new launcher will follow and be evolvable to lift more than 50 tons to low-Earth orbit.

The crew transportation vehicle will carry and support crew beyond low-Earth orbit. Extended stays are possible when docked to an in-space habitat or related capability.

The next generation launcher will launch from the new Russian Cosmodrome in Vostochny. The Cosmodrome is planned to be operational with the first launch of a Soyuz rocket in 2015.

Artist's rendition of the Space Launch System.

Artist's rendition of Orion and the upper stage of the Space Launch System.

Looking forward, enabling exploration missions will require critical contributions from many space agencies. While NASA and Roscosmos are developing a new generation of exploration systems, other space agencies are undertaking studies intended to inform individual decision making regarding exploration mission scenarios and agency roles. The ISECG Mission Scenario informs these studies.

Concordia: a Franco-Italian base in Anctartica used as a human exploration analogue.

Analogues to Simulate Exploration Destinations

A wide range of analogue sites and facilities are in use today by space agencies around the world to simulate exploration missions, helping prepare for exploration beyond low-Earth orbit. Agencies are regularly sharing information related to planning of analogue campaigns and lessons learned in order to maximize the usefulness of these activities.

Future missions, such as those envisioned in this Global Exploration Roadmap, will require new capabilities, techniques, and operational modes to be tested extensively in relevant environments to 1) confirm that systems will function as desired in relevant environments as well as revealing unanticipated behavior, 2) compare the performance of alternative combinations of systems and operations, and 3) train flight crews, ground support personnel, engineers, and managers.

Analogue activities are also extremely useful to the science community for interpreting data from past or ongoing missions. In addition to these technical roles, these analogue activities could be used, as recent experience has shown, to engage the public with interesting and exciting mission simulations well before actual missions take place.

Analogue activities can involve testing of scientific, technological, or operational questions. They can also span a continuum ranging from very focused, tightly controlled, single-purpose tests to multi-faceted, integrated combinations of scientific, technological, and operational features designed to simulate different phases of a mission. These activities require physical locations or facilities that can simulate some aspects of the mission environment in order to test the system or activity in question.

Since the first release of the Global Exploration Roadmap, agencies have conducted a number of successful analogue activities that represent meaningful steps toward readiness for future missions beyond low-Earth orbit. Several examples include:

Technology Development Analogue Tests. All agencies continue developing technologies that can be applied to near-term robotic activities. For example, JAXA conducted field tests of a small robotic rover to test new devices, such as a laser ranging imager, a laser induced breakdown spectrometer, and autonomous operations in the desert on the Izu-Oshima Island near Tokyo (see photo), where geological conditions are similar to either the Moon or Mars. As a key member in a public-private partnership for development of future space exploration technologies, ASI developed the Mars Terrain Demonstrator facility and the (Mars) Entry, Descent, and Landing facility. These ASI facilities are being used to test rovers and landing vehicles in a simulated Martian environment.

JAXA's small rover demonstration in volcanic region.

Critical systems to sustain human presence on other planetary bodies have been tested on Earth in preparation for validation by future robotic missions. In an analogue simulation that will inform future planetary surface missions, a team consisting of NASA, CSA, the Smithsonian, and the University of Mainz (Germany) conducted a 10-day series of simulations and tests of In-Situ Resource Utilization technologies and operations in Hawaii. The main test, conducted in 2012, included the Regolith and Environment Science and Oxygen and Lunar Volatile Extraction (RESOLVE) prototype. The RESOLVE instruments suite provided by NASA, and the Canadian drill and avionics mounted on CSA's Artemis Jr. rover, is an experiment package designed to find, characterize and map the presence of ice and other volatiles in almost permanently shadowed areas at the lunar poles. This simulation illustrates preparations for more sustainable missions by using local raw materials to offset supplies transported from Earth.

Exploration Mission Operations Simulations. In a series of simulations spanning 2011 and 2012, NASA's Research and Technology Studies team compared several different combinations of robotic devices, EVA personnel, and astronauts in small space exploration vehicles to learn about effective approaches to explore small near-Earth asteroids. These simulations also evaluated the most advantageous locations for members of the four-person crew, whether that was in an EVA suit, inside an exploration vehicle, or remaining at the deep space habitat. They evaluated the impacts of a communications time delay on Earth-based mission control personnel providing traditional support functions from different remote locations (NASA JSC and ESA ESTEC). Results from these simulations demonstrated that an EVA crew member is most effectively utilized in accomplishing high priority tasks.

In parallel to technological developments, agencies also carry out analogue activities focusing on science and techniques to improve knowledge of key human factors that could enhance the performance and reduce risks of future missions. Several examples include:

Simulations of Human Factors and Performance. A six-person crew, including three Russians, two Europeans and one Chinese, carried out a 520-day simulation of a human Mars mission, called Mars500 at the Russian Institute for Biomedical Problems in Moscow. The purpose of this study was to gather data, knowledge and experience to help prepare for a real mission to Mars. Sealed in a chamber in June 2010, the six crew members had only personal contact with each other plus voice contact with a simulated control centre and family and friends as would normally happen in a human space mission. A unidirectional time delay of up to 20 minutes was built into communications with the control center to simulate an interplanetary mission, and the crew was given a diet almost identical to that used for the ISS. The study helped to determine key psychological and physiological effects of living in such an enclosed environment for extended periods of time.

ASI, CNES, and ESA, in cooperation with the French Polar Institute (Institut Paul Emile Victor) and the Italian Antarctic Research Programme, are supporting a variety of human health and performance-related investigations in medicine, physiology and psychology, using the unique environment of Concordia Station (isolation, confinement, climate, hypoxia) as a human exploration analogue.

CNES, DLR, and ESA are supporting experiments in Moon gravity, Mars gravity, and micro-gravity on an aircraft flying parabolic trajectories (see photo below). These experiments address a wide range of research topics, with an emphasis on human health and performance. Beyond technological developments and research on human factors, agencies also carry out analogue activities focusing on science and techniques to analyze and characterize planetary science.

Analogue Tests of Science Operations and Techniques. CSA has conducted a series of multi-deployment analogue missions: 1) robotic detection of methane was tested at natural seeps in the Canadian arctic (Axel Heiberg Island) and within an abandoned mine (Asbestos, QC); 2) multi-platform exploration of underwater microbialites demonstrated novel imaging and communication technologies (Pavilion Lake, BC; in collaboration with NASA); and 3) deployments to Canadian impact structures (Mistastin, Sudbury) investigated how best to combine human and robotic capabilities for sample return selection.

Partial-gravity parabolic flights have recently been jointly conducted by CNES, DLR and ESA to simulate the Moon and Mars environments

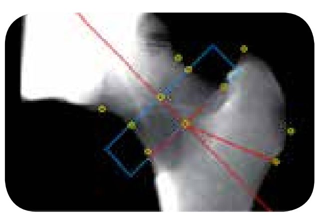
Agencies anticipate continued use of analogues comparable to those described here as part of a stepwise approach for implementing new capabilities needed for missions beyond low-Earth orbit: first technology and operations development on Earth, followed by proof of concept in analogue campaigns, then robotic mission validation, and finally incorporation into a human space exploration architecture.

Managing Health and Human Performance Risks for Space Exploration

Crew health and performance are critical to successful human exploration beyond low-Earth orbit. Long-duration missions and planetary operations bring numerous risks that must be understood and mitigated in order to keep astronauts healthy and productive. The main risk drivers are long-duration exposure to radiation and microgravity. In addition, onboard capabilities that allow for autonomous early diagnosis and treatment of injuries and disease processes are critical.

To address these challenges, agencies are actively performing studies in laboratories, ground analogues and on board the ISS. Much work remains to be done, and agencies are increasingly cooperating to enable timely answers in support of exploration mission needs. This is very important because with a common understanding of risks and effective mitigation approaches, agencies have the opportunity to leverage investments in the research or hardware development to mitigate risks.

Since crew health and performance are primary, critical concerns, the ISS partner agencies are actively seeking to use ISS research to extend human space mission durations while ensuring the crew remains healthy and able to perform well. The health risks are significant enough to drive decisions related to planning of exploration missions beyond low-Earth orbit. These are listed in the table on the next page. The “stoplight” chart gives a visual characterization of the current postures for these risks relative to several exploration mission scenarios.



Hip QCT monitors changes in hip bone structure (fracture risk assessment) on the ISS.

JAXA astronaut Akihiko Hoshide uses the advanced resistive exercise device on board the ISS.

The short arm human centrifuge at DLR enables hypergravity research to understand the gravity impacts on the human physiology and performance.

- **Red (Unacceptable):** A risk with one or more of its attributes (i.e., consequence, likelihood, uncertainty) currently exceeding established human health and performance standards for that mission scenario.
- **Yellow (Acceptable):** A risk with all of its attributes (i.e., consequence, likelihood, uncertainty) well understood and characterized, such that they meet existing standards but are not fully controlled, resulting in "acceptance" of a higher risk posture. Lowering the risk posture is important, but the risk is not expected to preclude a mission.
- **Green (Controlled):** A risk with all of its attributes (i.e., consequence, likelihood, uncertainty) well understood and characterized, with an accepted mitigation strategy in place to control the risk. It is still helpful to pursue optimized mitigation opportunities such as compact and reliable exercise devices.

Main Human Health and Performance Risks for Exploration	Not mission limiting GO	Not mission limiting, but increased risk GO	Mission limiting NO GO	**Mission**			
				ISS (6 mo)	**Lunar** (6 mo)	**Deep Space** (1 yr)	**Mars** (3 yr)
Musculoskeletal: Long-term health risk of early onset osteoporosis Mission risk of reduced muscle strength and aerobic capacity				Green	Green	Yellow	Red
Sensorimotor: Mission risk of sensory changes/dysfunctions				Green	Yellow	Green	Yellow
Ocular Syndrome: Mission and long-term health risk of microgravity-induced visual impairment and/or elevated intracranial pressure				Yellow	Yellow	Red	Red
Nutrition: Mission risk of behavioral and nutritional health due to inability to provide appropriate quantity, quality and variety of food				Green	Green	Yellow	Red
Autonomous Medical Care: Mission and long-term health risk due to inability to provide adequate medical care throughout the mission (Includes onboard training, diagnosis, treatment, and presence/absence of onboard physician)				Green	Yellow	Red	Red
Behavioral Health and Performance: Mission and long-term behavioral health risk				Green	Yellow	Red	Red
Radiation: Long-term risk of carcinogenesis and degenerative tissue disease due to radiation exposure—Largely addressed with ground-based research				Green	Yellow	Red	Red
Toxicity: Mission risk of exposure to a toxic environment without adequate monitoring, warning systems or understanding of potential toxicity (dust, chemicals, infectious agents)				Yellow	Yellow	Red	Red
Autonomous Emergency Response: Medical risks due to life support system failure and other emergencies (fire, depressurization, toxic atmosphere, etc.), crew rescue scenarios				Yellow	Yellow	Red	Red
Hypogravity: Long-term risk associated with adaptation during intravehicular activity and extravehicular activity on the Moon, asteroids, Mars (vestibular and performance dysfunctions) and postflight rehabilitation				Green	Green	Yellow	Red

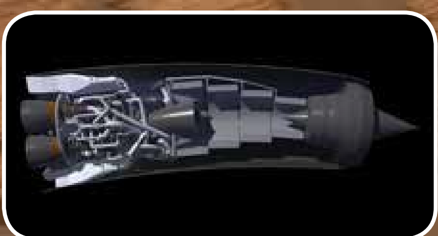
All of the identified risk areas are the subject of vigorous independent research activities across the international partnership. To take maximum advantage of the opportunity provided by the ISS, the partners agreed that an international approach to addressing these risks, using all available assets, was the best way to ensure readiness for global exploration. Existing working groups, such as the International Space Life Sciences Working Group, are being utilized to ensure a coordinated international effort. Agencies are increasing efforts to share operational medical and biomedical science data, standardize techniques and methodologies, share hardware and crew subjects onboard the ISS. These efforts are underway and a key to success.

In addition to research, the ISS provides the capability to validate countermeasures and mitigation strategies. Countermeasures used on the ISS are largely effective at managing health and performance risks. However, progress must be made before exploration missions can be successful.

Observation:

➔ Agencies should increase efforts to pursue a coordinated approach to mitigating the human health and performance risks of extended duration exploration missions, putting priority on efforts to reduce countermeasure mass and volume, and on driving risks to an acceptable level.

Chapter 5. Conclusion



The Global Exploration Roadmap reflects international efforts to define a pathway for human exploration of the solar system, with Mars as the ultimate 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 participating agencies to collaboratively develop exploration mission scenarios and coordinate their preparation.

Water Ice on Mars

Since its inception, space exploration has produced numerous benefits for humanity. Knowledge gained has driven scientific and technological innovation that continues to contribute to new products and services. The cultural and inspirational impact to people on Earth stimulates our curiosity and sense of place in the universe. Overcoming the challenges and realizing the capabilities needed to explore will bring nations together with the capacity to address mutual challenges and common opportunities.

Continuation of the Global Exploration Roadmap activity and development of coordinated national efforts will require considerable dialogue on how to align the policies and plans of participating space agencies, as well as address the intergovernmental considerations that affect its successful implementation. Decisions regarding implementation of specific mission scenarios will not be made by ISECG. They will follow national policy decisions and international consultation at multiple levels – informed by products (architectures, mission designs, etc.) developed collectively. In the coming years, many nations will be developing their domestic policy and legal frameworks to most effectively implement sustainable human space exploration.

Additionally, some agencies are engaged in dialogue with private sector entities who are beginning to move forward with plans to invest in projects 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 applicable legal mechanisms.

While this document does not create commitments of any kind on behalf of any of the participants, the Global Exploration Roadmap is an important step in an evolving process toward achieving a global, strategic, coordinated, and comprehensive approach to space exploration.

The key observations of the Global Exploration Roadmap that was released in September 2011 were a focus of attention over the last two years. The following new key observations are presented for consideration.

1. In order to build a sustainable human space exploration endeavour that lasts decades, agency leaders should maintain a focus on delivering value to the public.

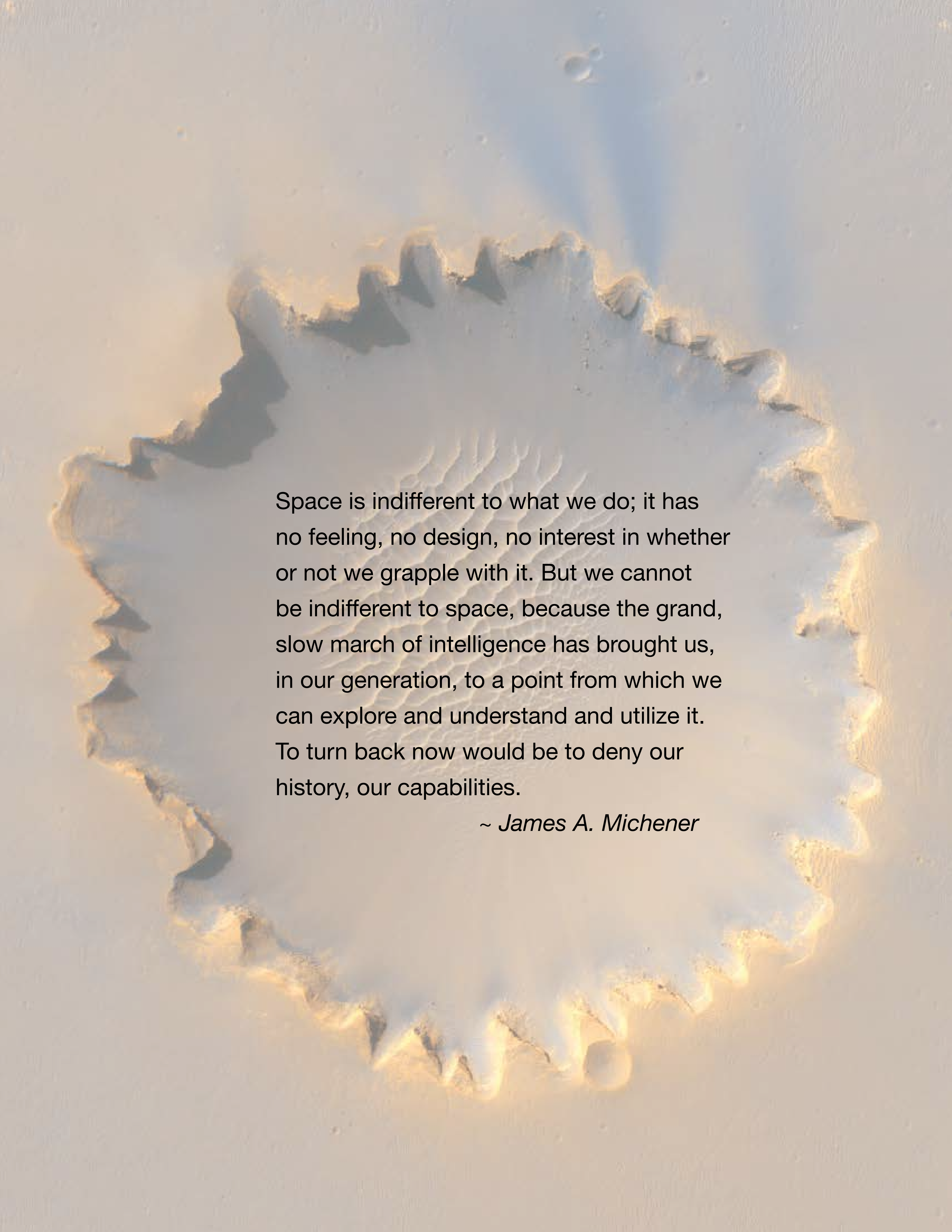
2. With the goal of enabling several partners to contribute critical capabilities to future human missions, agencies note that near-term collaborative missions on the ISS, in the lunar vicinity, on the lunar surface, and robotic missions may be used to simulate and better inform preparations for future international missions to Mars.

3. New mission concepts, such as human-assisted sample return and tele-presence should be further explored, increasing understanding of the important role of humans in space for achieving common goals.

4. Robotic science missions provide an important technique for obtaining the data needed to prepare for human exploration beyond low-Earth orbit. It is generally accepted by both the science and exploration communities that measurements and data sets obtained from robotic missions support both the advancement of science and preparation for human exploration.

5. Agencies should increase efforts to pursue a coordinated approach to mitigating the human health and performance risks of extended duration exploration missions, putting priority on efforts to reduce countermeasure mass and volume, and on driving risks to an acceptable level.

This and subsequent iterations of the Global Exploration Roadmap should provide the technical basis for informing the necessary binding agreements between agencies and governments.



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 utilize it.
To turn back now would be to deny our
history, our capabilities.

~ *James A. Michener*

ISECG
International Space Exploration
Coordination Group

The Global Exploration Roadmap is a nonbinding product of the International Space Exploration Coordination Group (ISECG). This second iteration will be followed by periodic updates as the content evolves and matures. ISECG was established by 14 space agencies to advance the Global Exploration Strategy by providing a forum where interested agencies can share their objectives and plans, and explore concepts that make use of synergies. 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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