The Global Exploration Roadmap

NASA/Kathy Laurini
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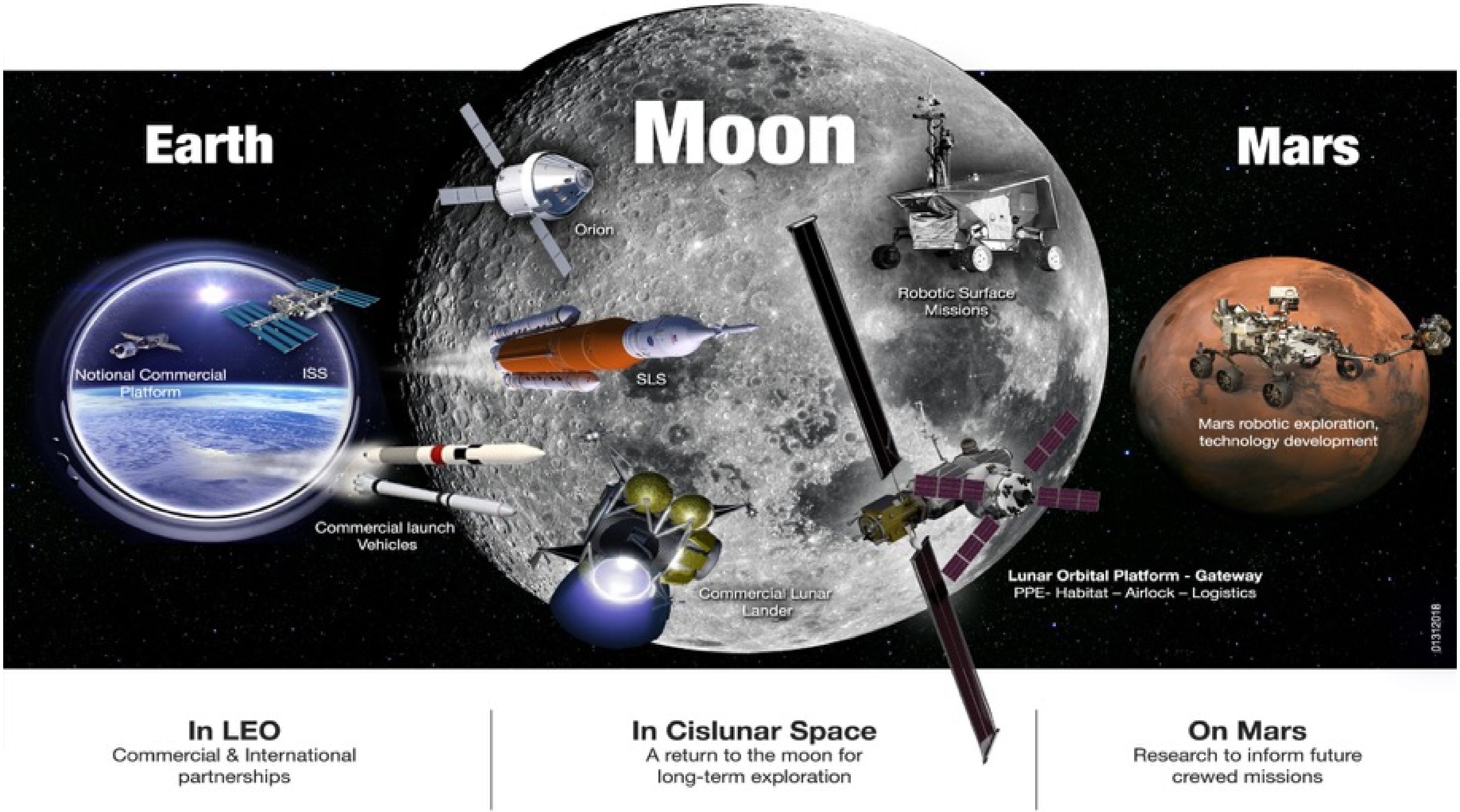
Space Policy Directive-1

"Lead an innovative and sustainable program of exploration with commercial and international partners to enable human expansion across the solar system and to bring back to Earth new knowledge and opportunities.

Beginning with missions beyond low-Earth orbit, the United States will lead the return of humans to the Moon for long-term exploration and utilization, followed by human missions to Mars and other destinations."

NASA's Exploration Campaign



ISECG Background

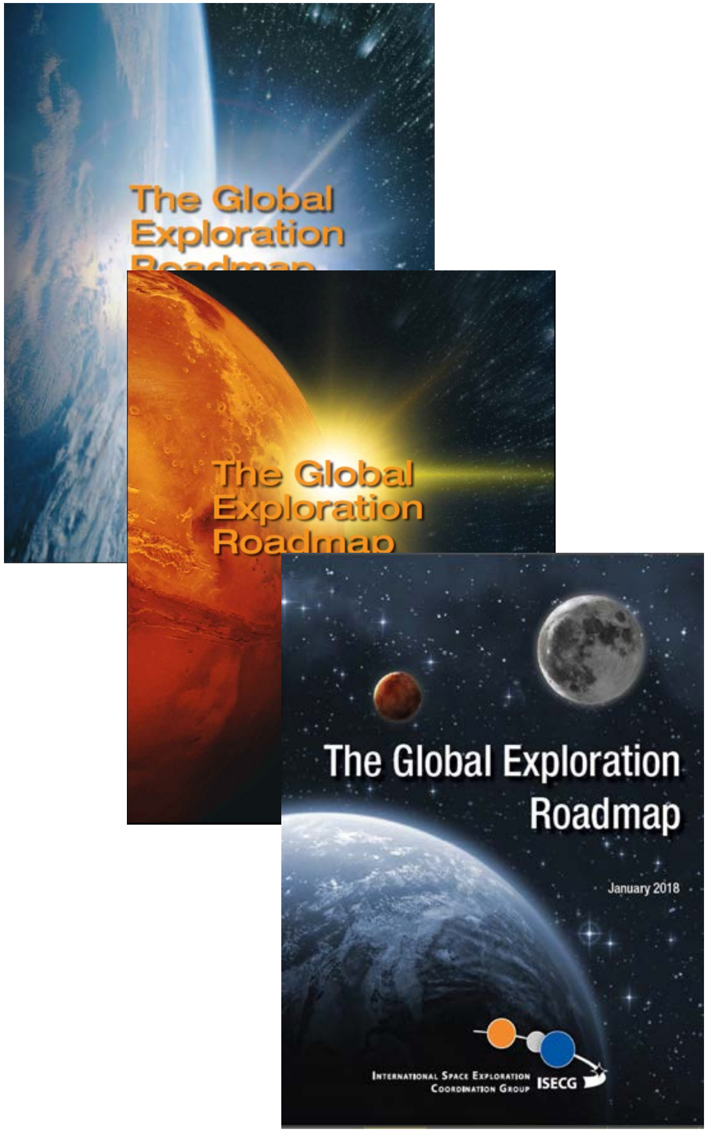
- **The ISECG is a voluntary, non-binding forum where participating space agencies share information and work together on products with the goal of strengthening individual agency exploration programs and the collective effort**
  - Human and robotic exploration of destinations humans may someday live and work
- **Established in 2007, rotating chairmanship**
  - NASA currently chairs ISECG
- **Avoid duplication with other forums**
- **Main benefits of participation**
  - Promotes discussions enabling a common understanding on aspects that will inform future human exploration related partnerships
  - Develops products which inform individual agency efforts and decisions
  - Facilitates agency efforts to leverage investments in human exploration preparation activities
  - Engages a broader set of agencies than ISS partnership

ISECG Participating Agencies

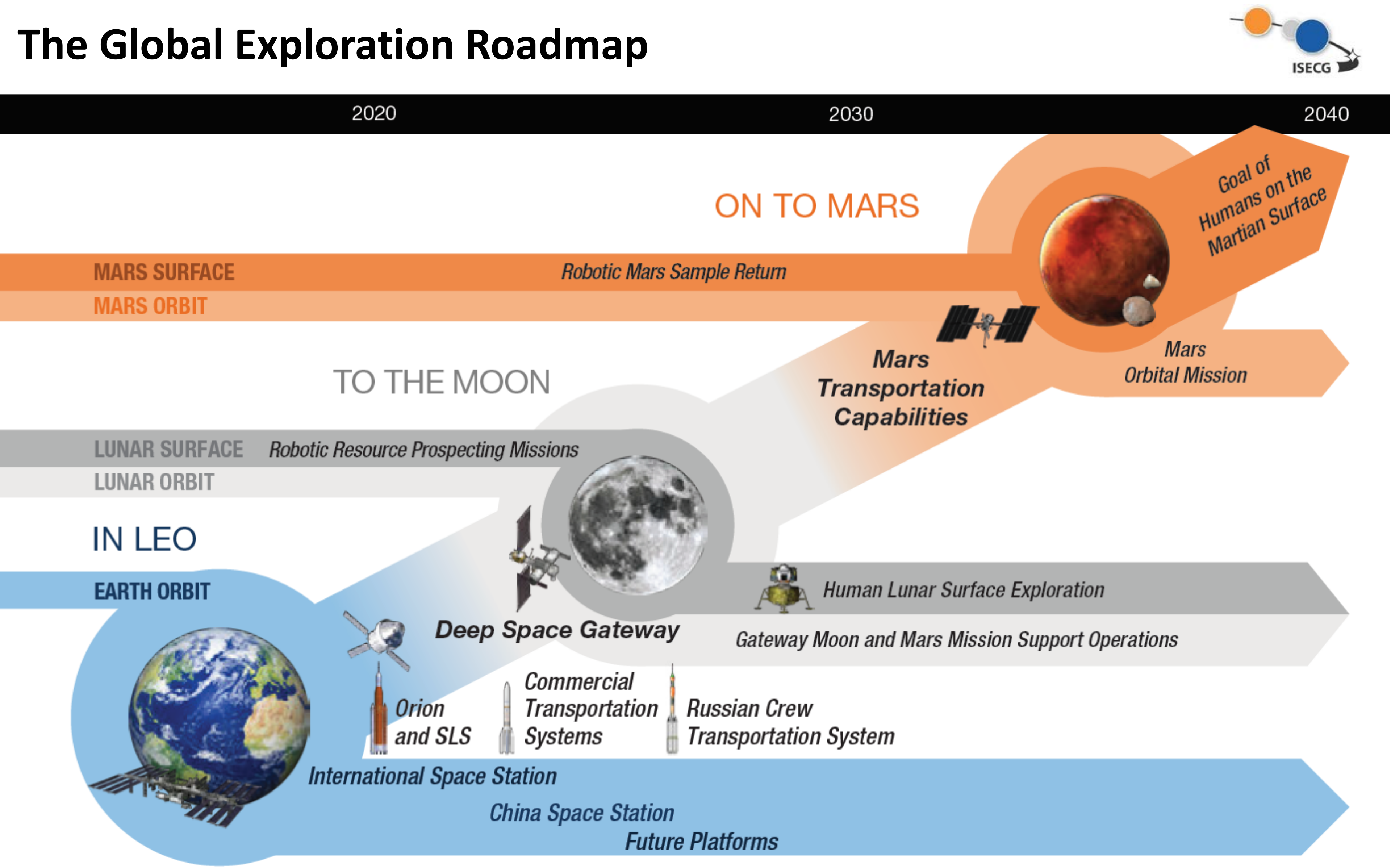
The Global Exploration Roadmap

- **The GER is a human space exploration roadmap reflecting consensus on expanding human presence into the Solar System and is intended to serve as a tool to help promote support for participation**
  - First released in 2011. Updated in 2013 and 2018

- **Discussions which led to the non-binding roadmap included**
  - Sustainability Principles
  - Importance of ISS and LEO
  - The Moon: Lunar vicinity and Lunar surface
  - Mars: The Driving Horizon Goal



The Global Exploration Roadmap



Common Goals and Objectives

- **Expand Human Presence into the Solar System**
  - Ensure continuity for human spaceflight and continued utilization of LEO
  - Enable sustained living and working around and on the Moon
  - Enable sustainable human missions living and working around and on Mars
- **Understand Our Place in the Universe**
  - Study the origin and evolution of the Earth and the Moon system, the Solar System and the Universe
  - Search for evidence of past or present life ad the origin of life on Earth
  - Investigate habitability of potential human destinations
- **Engage the Public**
  - Inspire and Educate
  - Create opportunities for participation in space exploration
  - Deliver benefits to society
- **Stimulate Economic Prosperity**
  - Promote industrial capability and competitiveness for space exploration
  - Facilitate the development of commercial markets at exploration destinations
  - Promote collaboration with the private sector
- **Foster International Cooperation**
  - Encourage and embrace the participation of nations in space exploration initiatives
  - Promote interoperability to increase opportunities for international cooperation

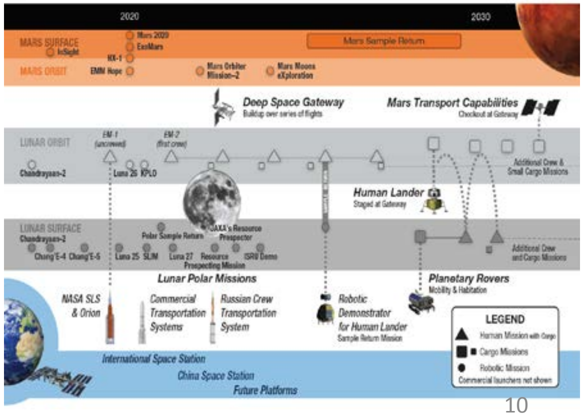
Benefits of Space Exploration

- **Exploration is a grand endeavor pursued by nations seeking to gain new knowledge, inspire and drive innovation**
- **Fundamental benefit areas described in the Global Exploration Roadmap**
  - Innovation and Economic Growth
  - Knowledge Gain
  - Global Cooperation: Partnership to Address Global Challenges
  - Culture and Innovation

Planned and Conceptual Human Exploration Missions

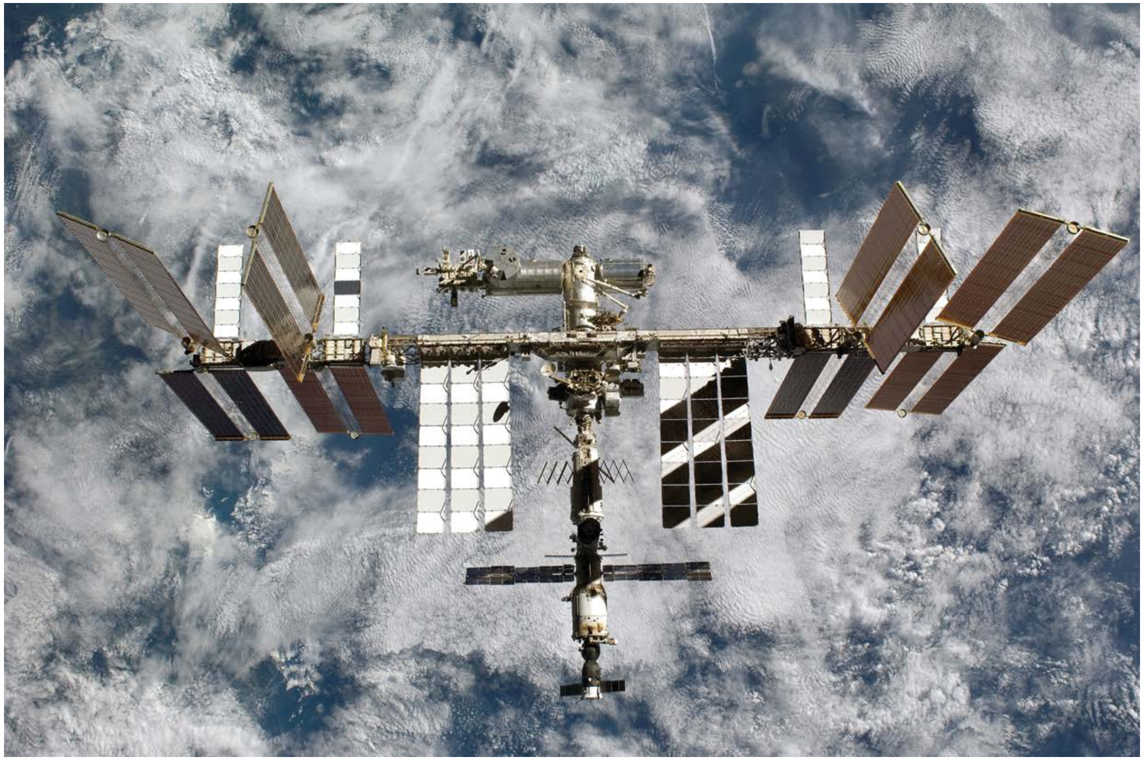
- **The Global Exploration Roadmap also contains a Mission Scenario which paints a picture of human and robotic exploration at the mission level, showing planned human and robotic missions in the next decade, as well as conceptual human missions which could follow**
  - Provides a reference for technology development and conceptual capability studies
- **The Mission Scenario contains a high level human lunar exploration scenario which has been worked in ISECG for the purpose of informing technology and conceptual study investments by interested**
  - Responds to common goals, objectives
  - Based on sustainability principles
    - Affordability
    - Exploration Benefit
    - Partnerships
    - Capability Evolution and Interoperability
    - Human-Robotic Partnership
    - Robustness

ISECG Mission Scenario



Low Earth Orbit will remain an important destination

- **International Space Station (ISS)**



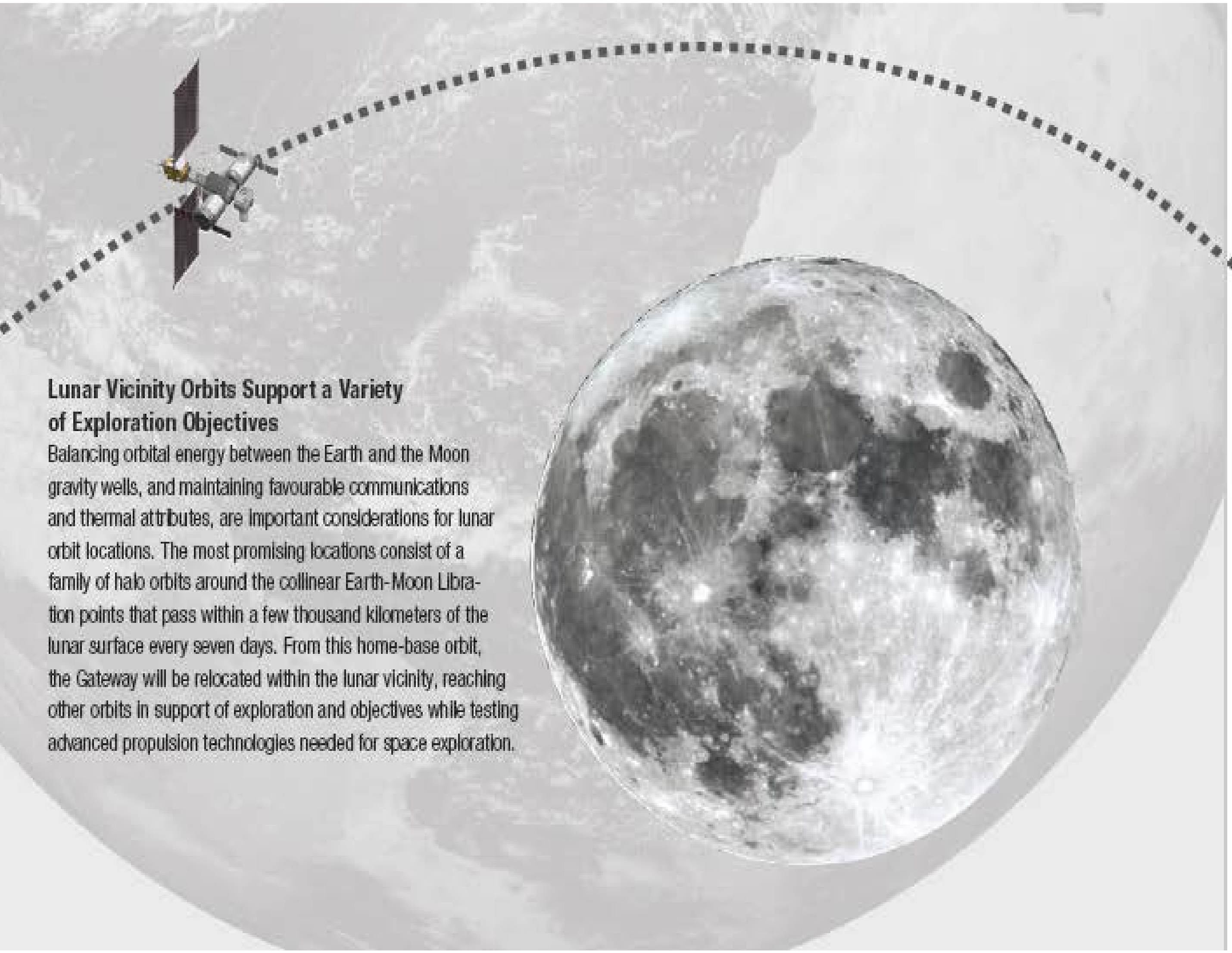
Water Recovery Tech Demo

Additive Manufacturing in Space

Human Research

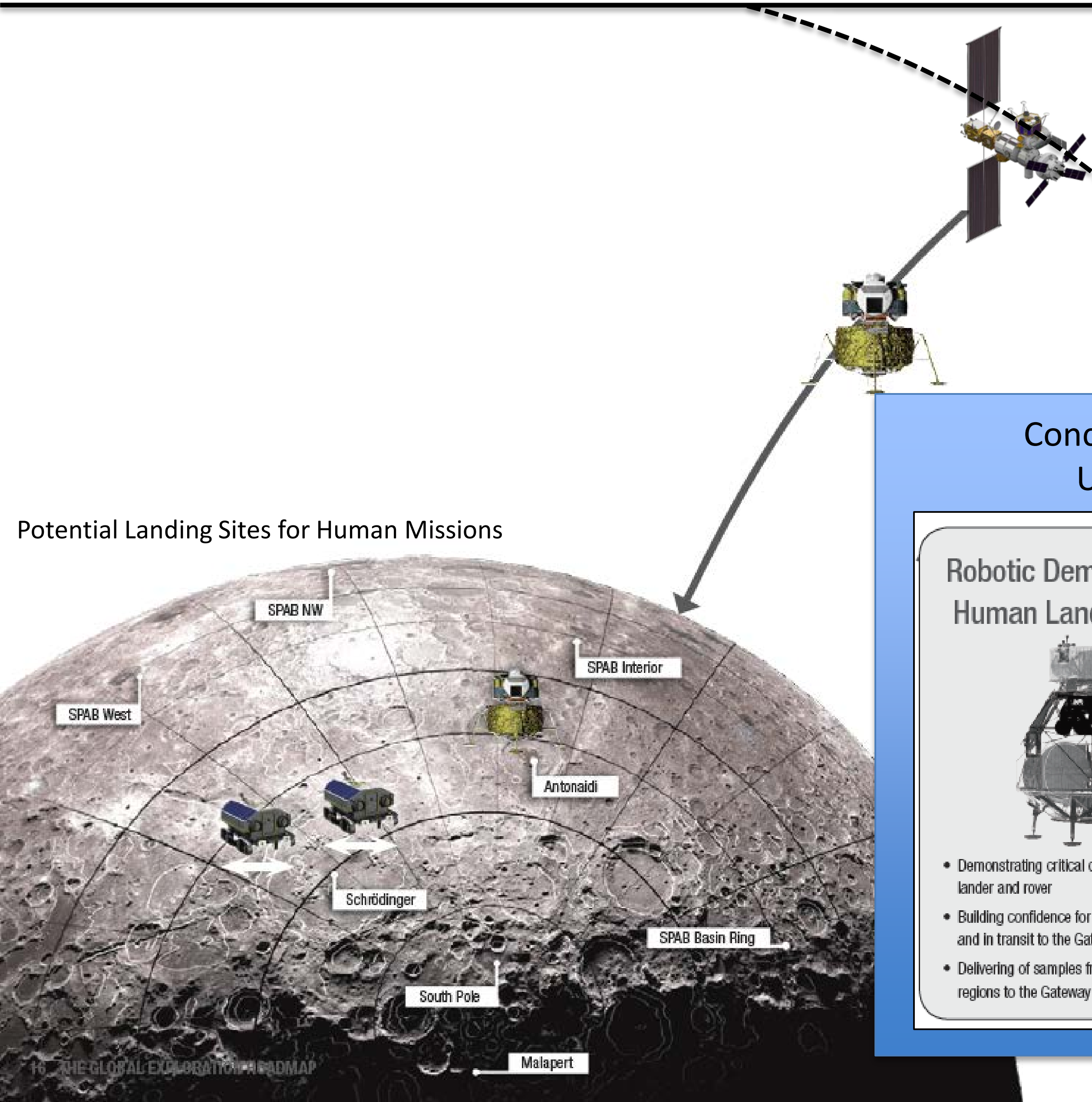
- **China Space Station**
- **Future Platforms**

Gateway in the Lunar Vicinity



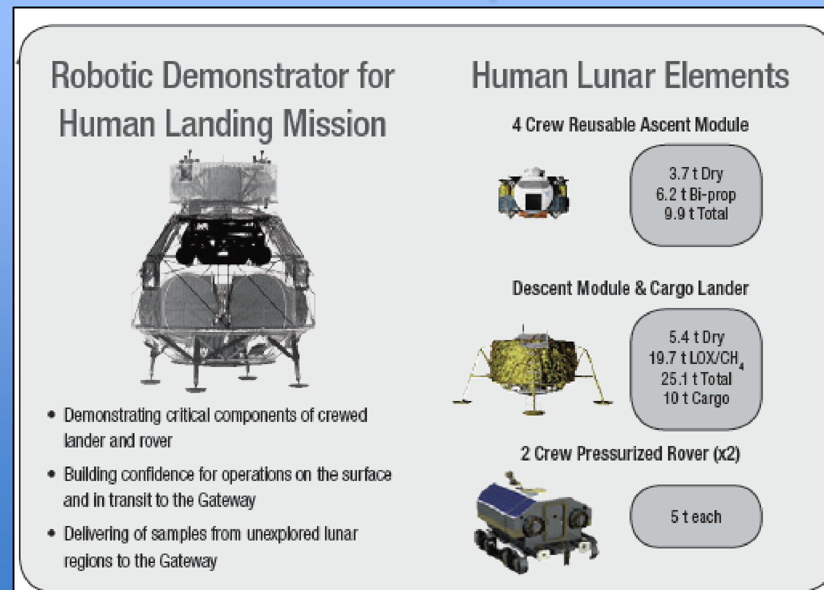
- **Gateway Enables:**
  - Reusability
  - Testing
  - Accessibility
  - Science
  - Proximity to lunar surface

A Conceptual Reference Architecture for Human Lunar Missions



Potential Landing Sites for Human Missions

Conceptual Human Lander and Rover Under Study by ESA, JAXA, CSA



Near-Term Opportunities for Coordination and Cooperation

- **Significant resources are being expended around the world to prepare for human space exploration**
- **Agencies seek knowledge on partner agency priorities and plans through international coordination**
- **Agencies seek opportunities to leverage investments in exploration through international cooperation**
- **GER3 Focused on these areas**
  - Private Sector Initiatives and Partnership Opportunities
  - ISRU and the Lunar Poles
  - Advanced Technologies
  - Human Health and Performance Risk Mitigation
  - Analogue Activities

Private Sector Initiatives and Partnership Opportunities

- **Private sector interest in economic development of Low Earth Orbit**

- **Global private investment in spaceflight activities increases the potential for new partnerships and availability of commercial services for beyond LEO**

- **The GER demonstrates agency support for two main areas of interest**
  - Joint government/private entity development of space capabilities
  - Commercial services, such as
    - Cargo to the Gateway
    - Communication
    - Delivery of instruments and logistics to the surface of the Moon and Mars

ISRU and the Lunar Poles

- **ISRU will make human exploration sustainable. Step-wise approach endorsed, beginning with prospecting then acquisition and processing demos before any architecture could rely on local resources**
- **Opportunity for coordination of lunar volatile prospecting activities benefits science and human exploration**

Future Lunar Robotic Missions

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

Preparatory Activities: Critical Exploration Technologies

- **Critical technologies identified and gap assessment underway**
- **Lunar exploration provides opportunity to drive technologies needed for Mars, such as:**
  - Enhanced Reliability Life Support
  - Solar Electric Propulsion and Power
  - Surface power
  - Extended mobility
  - Dust mitigation
  - ISRU

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

International Space Exploration Forum (ISEF2)

- **Second international government (Ministry)-level dialog on space exploration**
  - 45 countries and intergovernmental organizations, Tokyo, March 3, 2018
  - The first ISEF meeting was held in Washington, DC in January 2014
- **The purpose of ISEF is to enrich (government-level) understanding of the importance of space exploration for the benefit of humankind and further advance international cooperation and collaboration on space exploration through non-binding, high-level policy dialog**
- **Three products of ISEF2**
  - Joint statement, Tokyo Principles for International Space Exploration, ISEF Terms of Reference (http://www.isef2.jp/)

International Space Exploration Forum (ISEF2)

- **Key takeaways**
  - Extending exploration deeper into the solar system, from LEO through the Moon to Mars and beyond, is a goal widely shared by the international community
  - Importance of building sustainable human exploration as well as robotic by making the most of each step
  - ISS is a platform for scientific research, technical demonstration, and experimentation for exploration of outer space and act as a project of peaceful international cooperation
  - Heralded the new landscape of modern exploration characterized by significant contributors on every continent, in both the public (governmental) and private (commercial and non-governmental) sectors, and among accomplished space-faring nations as well as those countries just beginning to explore and utilize outer space--encouraging wider opportunities for innovative partnerships of these contributors
  - Highlighted ISECG GER, recognized the importance of international cooperation on space exploration in LEO and beyond LEO

Conclusion

- The updated GER will serve as a tool to help agencies collaboratively prepare for future human space exploration missions and partnerships
- ISS partner agencies have been strong participants in the roadmapping process since 2010, and participating in Gateway formulation studies since 2014
- Additional agencies interested in contributing to the global effort
- An innovative and sustainable program of exploration needs international partners to enable human expansion across the solar system and to bring back to Earth new knowledge and opportunities
- Growing capability and interest from the private sector indicates a future for collaboration not only among international space agencies, but also with private entities pursuing their own goals and objectives
- The GER demonstrates that our international partner space agencies want to be important stakeholders from the beginning of exploration beyond LEO