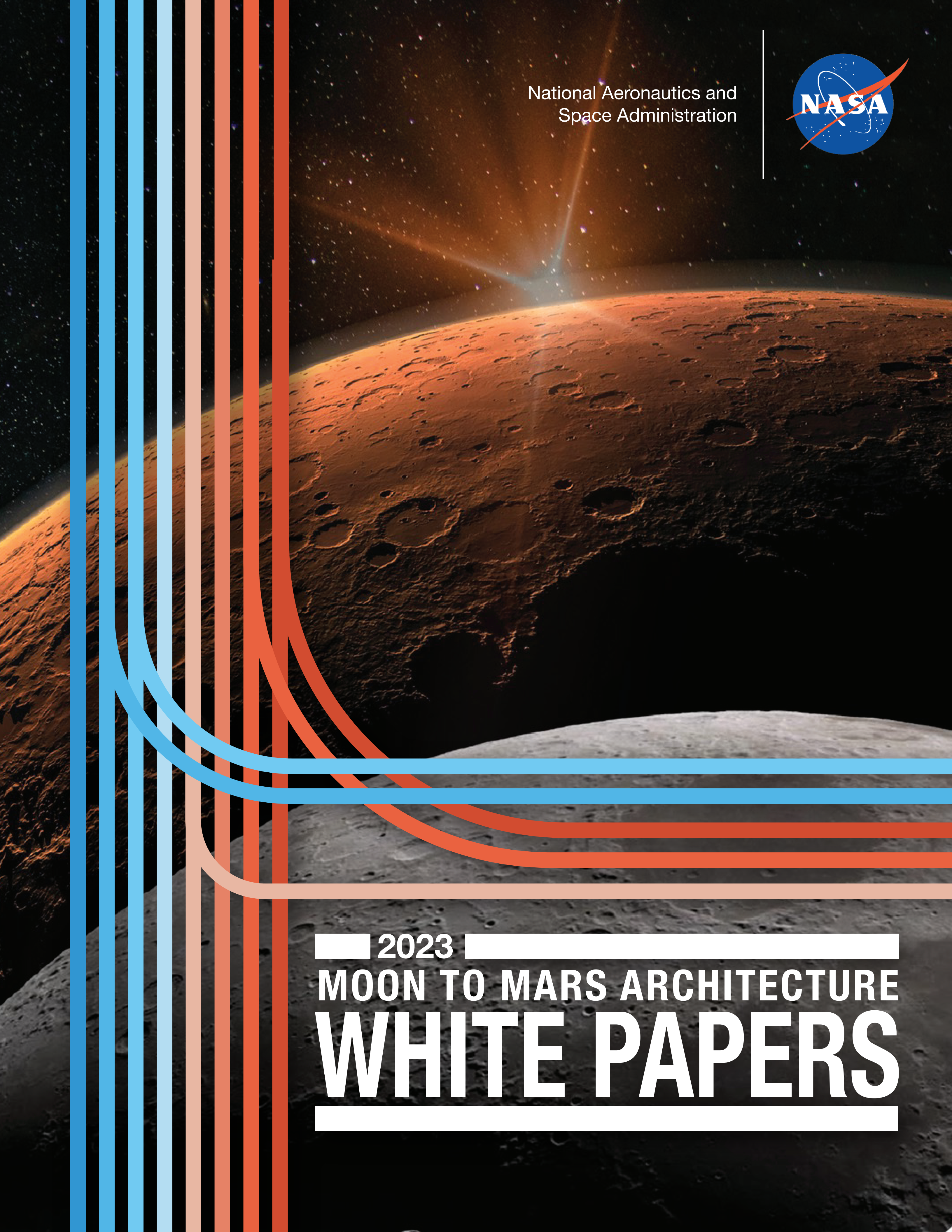


National Aeronautics and
Space Administration

2023

MOON TO MARS ARCHITECTURE
WHITE PAPERS

2023 *White Papers*

White Papers written in response to suggestions at 2023 Moon to Mars Architecture workshops.

4. **Surface Extravehicular Activity Architectural Drivers**

When humans return to the Moon, they won't simply land — they'll explore the lunar surface during extravehicular activities, or spacewalks. NASA and its partners will need to address the unique challenges of walking on the Moon. The lessons learned on the lunar surface will directly influence plans for crewed Mars missions.

9. **Lunar Communications and Navigation Architecture**

NASA's return to the Moon will require reliable communications services and accurate navigation data. A network of ground stations, space relay satellites, and surface-to-surface communications equipment provided by NASA, industry, and international partners will keep Artemis astronauts connected with Earth.

14. **Lunar Logistics Drivers and Needs**

To support crewed missions, the missions need numerous logistics items — the equipment and supplies necessary to sustain life, maintain systems, and conduct science — supplied to the lunar surface. The composition and amount of these items vary significantly based on mission requirements.

17. **Lunar Site Selection**

Exactly where Artemis missions land when humans return to the Moon will depend on a wide variety of factors. Surface conditions, science objectives, the lighting environment, communications availability, system capabilities, and more can affect landing site selection.

22. **Safe and Precise Landing at Lunar Sites**

Precision lunar landings will become increasingly important as space agencies and private companies explore more of the Moon. More precise landings enhance crew safety, minimize site contamination risks, and enable missions to reach specific, scientifically significant sites.

27. **Analytical Capabilities In-situ vs. Returned**

Samples collected on the lunar surface may be analyzed by science instruments launched to the Moon or at laboratories on Earth. In-situ analysis is limited by the capabilities of instruments that can be launched to the Moon, whereas samples returned to Earth can benefit from more refined analyses. However, returning pristine samples — those kept in the environment in which they were collected — to Earth presents technological challenges.

In January 2024, alongside the release of an update to the Architecture Definition Document, NASA published 13 new white papers on select Moon to Mars Architecture topics as part of the annual Architecture Concept Review cycle. Experts from across the agency authored the papers; some topics arose from suggestions at workshops for industry, academia, and international space agencies. The white papers explore the challenges of crewed missions to deep space and raise questions that need to be answered to build a future among the stars.

Mars Mission Abort Considerations

Crewed Mars missions have more challenging abort factors than lunar missions due to the sheer distance from Earth. An abort in transit to Mars will take months, not days. Early Mars missions will have limited abort options from the surface. This paradigm shift will require fundamental changes in mission planning.

Mars Communications Disruption and Delay

Communications blackouts and delays are unavoidable for crewed Mars missions, though blackouts can be mitigated through thoughtful design. Crewed Mars exploration must respond to the unique constraints of the Red Planet; to account for disruption and delays, system and crew autonomy must be a significant focus in mission planning.

Mars Surface Power Generation

The first human explorers on Mars will need energy to power the systems they use to live and work on the surface and ascend back to orbit. The Martian environment poses unique challenges for generating power and power requirements will vary significantly based on mission profile.

Key Mars Architecture Decisions

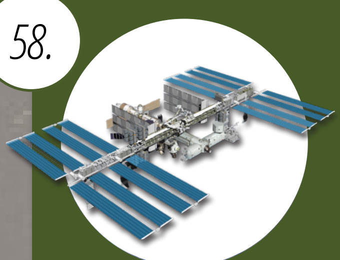
NASA has developed analysis tools to better understand the relationships between the many decisions it will need to make to begin planning initial crewed missions to Mars. Using these tools, seven key Mars architecture decisions have been identified. They are not the only questions to answer, but their answers will affect the many decisions that follow.

Human Health and Performance For Mars Missions

Astronauts on missions to Mars will face a series of interrelated risks to their health and performance, including radiation exposure, changing gravity, isolation, distance from Earth, and environmental factors on the surface. Mission architecture and equipment design should consider these risks and minimize them wherever possible.

Round Trip Mars Mission Mass Challenges

Round-trip Mars missions are much more difficult than one-way trips. Mars "gear ratios" are multipliers of the mass required to launch any given payload from Earth's gravity well to Mars' and then return it home. The mass requirements for each leg of a round-trip mission will affect mission cost, schedule, and complexity.



Exploration Lessons Learned from the Space Station

The International Space Station is humanity's testbed in low-Earth orbit. The orbiting laboratory is advancing capabilities in life support, navigation, extravehicular activities, and human health. Lessons learned on the space station are enabling deep space exploration.

Read the white papers here:
https://go.nasa.gov/3TM8c9y

Surface EVA Architectural Drivers

I. Introduction

Key elements of NASA's Moon to Mars Objectives for expanding humanity's presence beyond low-Earth orbit will require surface-based, partial-gravity extravehicular activities (EVAs). Surface EVA needs affect many aspects of the exploration architecture, including EVA suit subsystems, such as suit or pressure garment mobility, the portable life support system, and the informatics system; and external systems, such as habitation modules and surface mobility platforms.

Lunar surface missions take place in harsh environments with additional challenges, including limited resources/consumables resupply, communications delays, navigation, and lighting, depending on landing location and terrain. Suited activity on the Moon introduces multiple factors that drive the broader architecture, including dust intrusion, partial gravity, atmospheric pressures, logistics, pressurized volumes, site planning, contingencies, and human access to and from the lunar surface from various habitable elements. This paper highlights several key considerations related to lunar surface exploration EVAs that will be addressed in the Moon to Mars Architecture.

2. Dust (Regolith) Mitigation

An integrated strategy for lunar dust mitigation should include testing on Earth using simulants and the use of lunar experiments to characterize dust properties and build an understanding of polar regolith behavior. Dust in the polar region will be impacted by the unique natural environment: electrostatic charging can cause dust to adhere to surfaces, dust particles take longer to settle than on the Earth, and stirring/movement can remobilize dust particles.

Ground testing faces environmental limits. Convective flows typically dominate non-vacuum ground testing, making it difficult to replicate expected polar region electrostatic behaviors. Ground testing also typically requires multiple simulants, since no one simulant captures all the properties of lunar soil or the variety of soil compositions that astronauts might encounter.

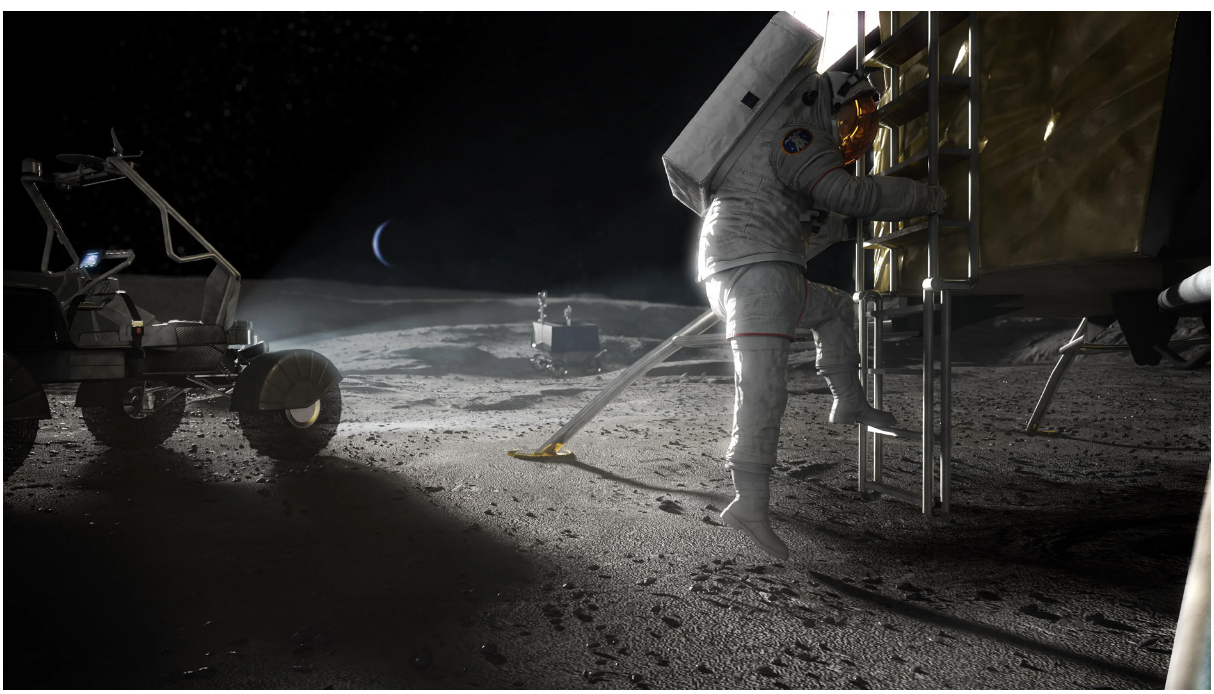


Figure 1. *Conceptual Rendering 1*

Most of the dust that poses a danger to system hardware and human health will also not be visible to the naked eye.

A successful mitigation strategy will both minimize dust intrusion and control dust at the interface with critical systems (including human dust exposure).[1] While human lungs are the most sensitive organs to dust exposure, dust can also have ocular and skin effects. NASA used research findings to derive a permissible exposure limit that defines acceptable lunar dust exposures and size fractions of physiological concern. Lunar dust adherence and transport into the habitable environment by EVA suits, tools, equipment, and payloads is difficult to predict. The amounts vary depending on the method of ingress/egress and mitigation methods/tools available to the crew.

Mechanical components of environmental control and life support systems, including vents, fans, intakes, and louvers, must be designed with dust intrusion in mind. Crew cabin systems and EVA systems adversely affected by dust include food preparation, medical implements, hygiene, filters, vacuum cleaners, seals, crew time, cameras, windows, lights, quick disconnects/connecters, switches, hatch seals, and more.

During the Apollo Program, the Lunar Module had direct crew access, with no intermediate airlock volume. Apollo crews complained of dust intrusion into the Lunar Module in almost all Apollo missions, and in some cases, dust was observed within the Command Module after on-orbit docking. The Artemis missions will develop operations to reduce dust intrusion, develop mitigation methods to reduce dust adherence and clean up/filter intruded dust, learn from the implementation of this development, and evolve as the missions progress.

3. Partial Gravity

Performing EVAs with differently sized crewmembers in partial gravity influences the design of the suits and accompanying architectures (especially sizing, mobility, and mass), science and logistics payloads that must be operated by crewmembers, and tools for performing geological/maintenance activities.[2] Some tasks will require the crew to navigate up and down slopes, traverse into and out of craters, and deploy surface payloads. Tasks beyond collecting geological samples could include vehicle maintenance, cargo/logistics transfer, and other physically demanding activities. Tasks to be performed by the EVA crew — such as riding in a rover, hammering, or climbing — drive specific interfaces and suit mobility features.

The suit architecture and interfaces with surface elements must accommodate a wide range of crewmember sizes. These requirements drive the design of the suit and attached hardware, vehicle interfaces, the types of crew actions and motions during EVAs, direct physical interactions with the lunar surface, and the total number of EVAs. Finally, systems will have to accommodate different prebreathe protocols than Apollo or microgravity prebreathe.[3]

4. Atmospheric Pressures

A fundamental limitation of human physiology when preparing for and conducting EVAs is the potential for acute and chronic injury from decompression sickness caused by pressure transitions. It is necessary to control the transition from the habitable volume's saturation atmosphere to the EVA suit's pressure, which is set lower to improve the crewmember's ability to operate and maneuver in the suit. This transition is managed in part by an oxygen prebreathe using a combination of the vehicle's atmosphere and the suit's pressure.

The amount of time necessary for this prebreathe is directly proportional to the difference between vehicle saturation and EVA pressures. While physiologically necessary, crew time spent engaged in prebreathe affects EVA operations and the risk of decompression sickness and can affect the duration of the EVA itself. Prebreathe studies help minimize prebreathe durations, allowing for increased utilization and completion of objectives performed by the crew during EVAs.

This choice of alternative atmospheric parameters in the vehicle (as opposed to relying on the suit and implementations thereof) may pose significant issues, including vehicle design challenges, such as reduced effectiveness for atmosphere-based avionics cooling, increased flammability, and more.[4] The suit and supporting architectures will also have the capability to perform decompression sickness treatment functions during the EVA if they are required for crew safety.

5. Commodities and Logistics

Elements that provide EVA capability include the architecture to recharge suit consumables (e.g., power, oxygen, water, CO_2 removal) and the ability to reserve suit consumables while connected to the vehicle via umbilical during activities such as prebreathe, suit checkouts, and pre- and post-EVA. The interfaces between the suits and the vehicles/elements must use common hardware to ensure compatibility and reduce astronaut training time and vehicle reconfiguration time.

Given the constraints for landed surface mass, different exploration architecture solutions will have varied impacts on commodity usage (such as the amount of air required to repressurize the habitable volume, depending on the ingress/egress method), in addition to the quantities used in the EVAs themselves. Suit maintenance must take place in a habitable pressurized environment.

Transferring logistics and consumables from logistics landers to habitable elements also presents a major challenge. The presence or absence of existing lunar

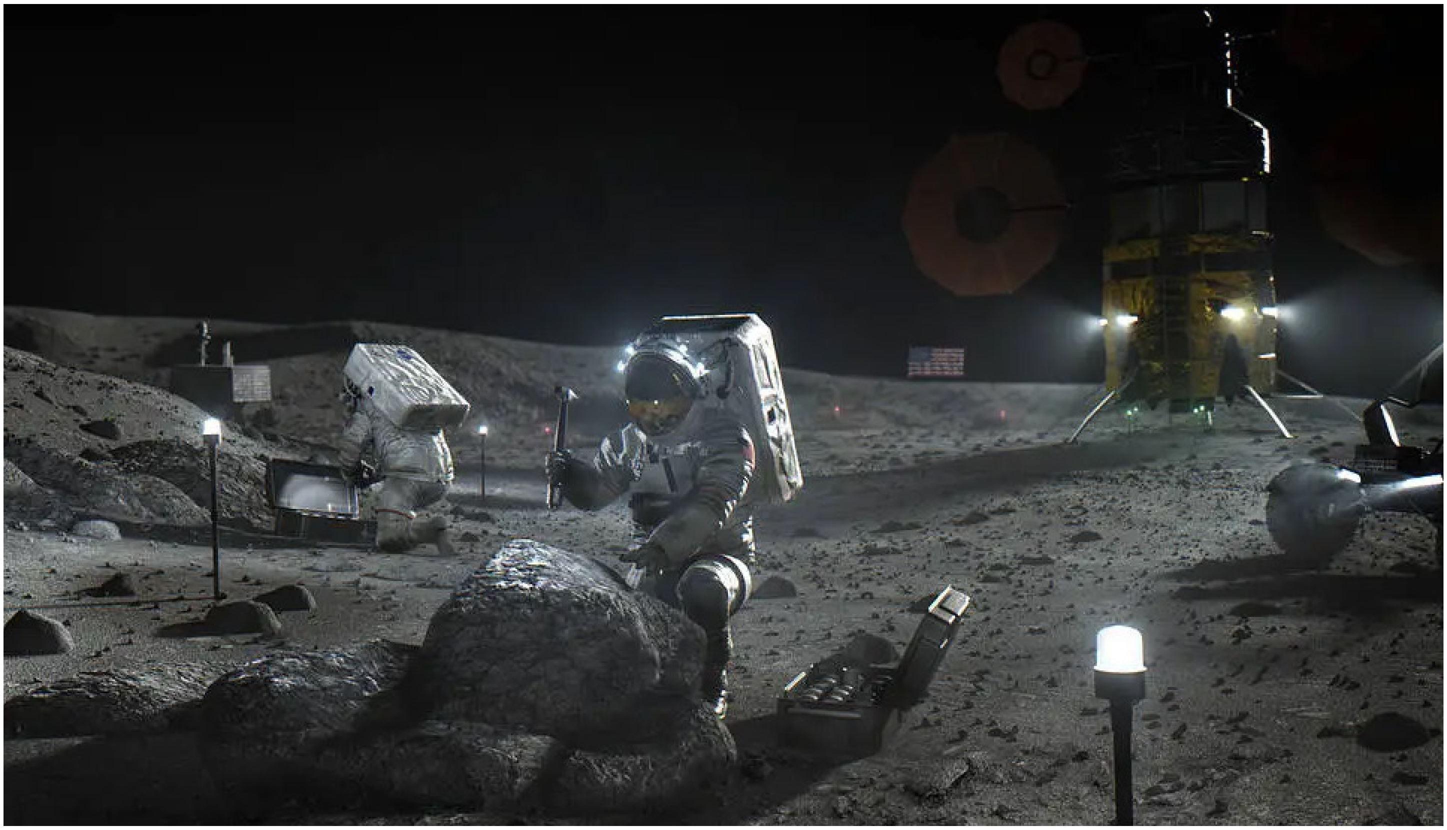


Figure 2. *Conceptual Rendering 2*

surface infrastructure, such as hardware for logistics transfer, is also an architecture driver since the EVA system may have to make up for any shortcomings in existing assets. The goal is to minimize logistics transfer in EVA timelines and maintain utilization objectives during EVAs.

6. Habitation and Pressurized Volumes

For both mobile and permanently emplaced surface habitation, layout and volume are important factors in the acceptability of the cabin interior. Crewmembers will require adequate internal size, in terms of both volume and surface area, to perform mission tasks safely and efficiently. This includes sufficient space to allow crewmembers to don/doff the suits in parallel, perform maintenance, volume for spares/logistics, and gather items needed to perform the EVA objectives.

For example, rear-entry suits require volume above the helmet to allow crewmembers to climb into their suits. Once suited, acceptable volume will be needed for EVA airlock hatches to swing open and closed, creating keep-out zones. Both mobile and permanently emplaced elements must also be designed for EVA compatibility. This includes access to any worksites, hatch sizes, sharp edges, thermal touch temperatures, and other factors.

7. Variations in Architectural Solutions for Ingress/Egress

An airlock could provide a separate volume from the main cabin to facilitate surface access. As such, airlocks provide a significant opportunity to control or propagate backward and forward contamination.[4,5] While other ingress/egress architecture solutions could help with dust intrusion, consumables, and other drivers listed in this paper, they also pose significant challenges to vehicles and suit architectures such as mass and volume.[6]

8. Enabling Suited Crew Decision-Making

Distributing work functions among Earth-based assets and mission assets, enabling an Earth-independent architecture, will be a profound architectural driver. Earth independence starts by giving crew members, particularly during EVA, the capacity to make informed decisions by interacting with and acting upon locally sourced information. Achieving this feat will not only be a technological accomplishment that advances suit capabilities but would also establish a fundamentally new medium of communication and information exchange between mission assets and Earth-based support.[7,8,9]

Earth-independent crew decision-making currently faces multiple challenges, such as establishing a highly integrated network of data-sharing among mission assets (from different vendors); rendering a variety of data in meaningful and contextually useful ways for crew consumption, interaction, and understanding; and aligning the broader flight operations structure (across NASA and service vendors) with the appropriate function allocation.[10,11]

9. Communications, Navigation, and Lighting

Communications between EVA crewmembers may be limited by distance and/or line of sight to each other and other surface assets during certain periods of initial surface missions because of architecture constraints and the potential for contingencies/walk-back scenarios. Surface mobility assets and other surface elements with Earth communications capabilities will allow the crew to explore further from the landing site, increasing utilization destination options.

Early missions will mainly utilize orienteering for navigation. Guidance and navigation systems, displayed via informatics and mobility assets, will help crew members get to destinations and back, guiding them to targets specifically designated by the science team.

The crew will experience persistent long shadows near the lunar South Pole, while also having the Sun directly in their field of view. To traverse safely and effectively across lunar terrain and slopes and into shadowed regions, the crew will use lighting sources (e.g., helmet lights and lights strapped/mounted to a crewmember or placed near the worksite), which can drive power needs. Thermal control performance in dark shadows will also affect EVA duration.

10. Site Planning

While missions to the lunar South Pole are being planned, design reference missions also include the capability to perform missions globally. Performing multiple missions to the South Pole and different regions of interest within range of each other will require strategic site planning. Several factors, such as ability to navigate difficult terrain while in a spacesuit, interactions required between surface elements, and safety will affect the integrated arrangement and configuration of surface elements to accomplish mission objectives. Mission designs will also need to address environmental factors (e.g., terrain, illumination, distance, plume) in concert with surface asset capabilities (e.g., rovers, habitats, landers, driving range, charging) and EVA capabilities (e.g., walk-back distance, vision), all while protecting the EVA crew.

Lunar surface selection of the site location of the surface elements must, of course, accommodate EVAs to perform science and utilization, maintenance, logistics, observations, and traversing during short-term missions, long-term stays, and sustained operations. This requires monitoring surface operations effects and management of habitation.

EVA ranges must be considered when planning distances between stationary elements to provide the crew access to a pressurized safe haven within the limits of emergency consumables in the event of a suit failure or medical event. Along with other considerations (i.e., landing accuracy, plume/surface interaction), distances the mobility elements can be driven or teleoperated before requiring charging affects the mission's mass requirements and must be balanced with operational needs such as EVA preparation, EVA duration, crew time, and crew sleep.

11. Contingencies and Operations

Ensuring crew safety is the most important aspect of planning human space missions. Risks such as system complexity, suit exposure, dust intrusion, EVA overhead times, vehicle failures, distance from a safe haven, and more can factor into the possible loss of crew or mission and must be considered in capability assessments. A vehicle/suit failure could result in scenarios where crew must walk back to a safe haven.

Hardware and human failures can lead to contingencies or incapacitation on the lunar surface, ultimately requiring assistance during EVA. Incapacitation requiring continuous full assistance is a risk that may need additional loading, transport, and lift capabilities, all of which affect suit design.

12. Conclusions

Surface EVA exploration has a significant number of architectural drivers that differ from microgravity. These differences include dust, the challenge of operating in partial gravity, mobility and habitation architecture, site planning, and contingency scenarios. Architectural challenges for surface EVAs result from limitations to mass, power, volume, the environment, and physical operations that occur on the Moon and, to even greater extent, on Mars.

Figure 3. *Conceptual Rendering 3*

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NASA's Lunar Communications and Navigation Architecture

I. Introduction

NASA's Artemis missions will return humanity to the Moon, establishing a long-term presence there and opening more of the lunar surface to exploration than ever before. This rapid growth of lunar activity requires robust and resilient communications, navigation, and networking capabilities for crew safety, command and control of spacecraft, return of science data, and precise maneuvering of assets in space and on the lunar surface.

Within the Moon to Mars Architecture,[1] the Communications, Position, Navigation, and Timing (CPNT) sub-architecture details the specific CPNT systems, functions, and use cases required to meet the NASA's Moon to Mars Objectives throughout each segment of the architecture. The CPNT sub-architecture through the Human Lunar Return segment — approximately through Artemis V — is detailed here.

The architecture development effort utilizes an objectives-based approach that focuses on the ultimate goals of human exploration of the Moon, Mars, and beyond.[2] The three objectives most fundamental to the CPNT sub-architecture are:

- Develop a lunar surface, orbital, and Moon-to-Earth communications architecture that scales to support long-term science, exploration, and industrial needs.
- Develop a lunar position, navigation, and timing (PNT) architecture that also scales to support long term science, exploration, and industrial needs.
- Preserve and protect representative features of special interest, including the shielded zone of the Moon.

II. Lunar Communications Architecture

The CPNT sub-architecure enables communication and navigation on the lunar surface, in cislunar space, and with Earth. Use cases allocated to the CPNT sub-architecture include:

- Crew voice and data communications.
- Video for scientific data collection, public outreach, and crew safety.
- Science data transmissions across:
  - » Direct-to-Earth communications.
  - » Communications among surface assets, orbiting relays, and Gateway, NASA's lunar-orbitting space station.
  - » Lunar surface-to-surface communications.

PNT use cases include providing position and timing of lunar samples, to crew navigating the surface, for landings and ascents, and to other cislunar assets. NASA will lead a distributed team of government, commercial, and international partners to implement the CPNT sub-architecture on Earth, in cislunar space, and on the lunar surface.

Cooperation among multiple service providers and users across government, industry, and international partners requires coordination and planning through established and new interface and operations standards. This will enable a long-term, scalable, and interoperable architecture that provides communications services across all the assets.

Beginning with the initial Human Lunar Return segment of the architecture, a variety of interface standards will enable interoperability. These include the LunaNet Interoperability Specification, the International Communication Systems Interoperability Standard, terrestrial wireless cellular standards, and other similar coordination with industry and international partners.[3,4,5]

LunaNet is an internationally coordinated framework for lunar interoperability, envisioned as a set of cooperating networks providing communications, navigation, and other services for users on and around the Moon. The LunaNet concept is based on a structure of mutually agreed-upon standards, protocols, and interface requirements that enable interoperability.

The International Communication Systems Interoperability Standard was developed to enable collaborative operations. These systems provide end-to-end compatibility and interoperability between a cislunar space platform, visiting spacecraft, lunar systems, and Earth.

Figure 1 illustrates the principal CPNT architecture during early exploration segments, including Human Lunar Return.[6] Ground stations from multiple providers offer connectivity direct to the lunar surface and to communications relays or assets in lunar orbit. Surface communications occur between crew and landing vehicles using a wireless network. Equipped surface assets communicate with Gateway and via orbital relays to Earth.

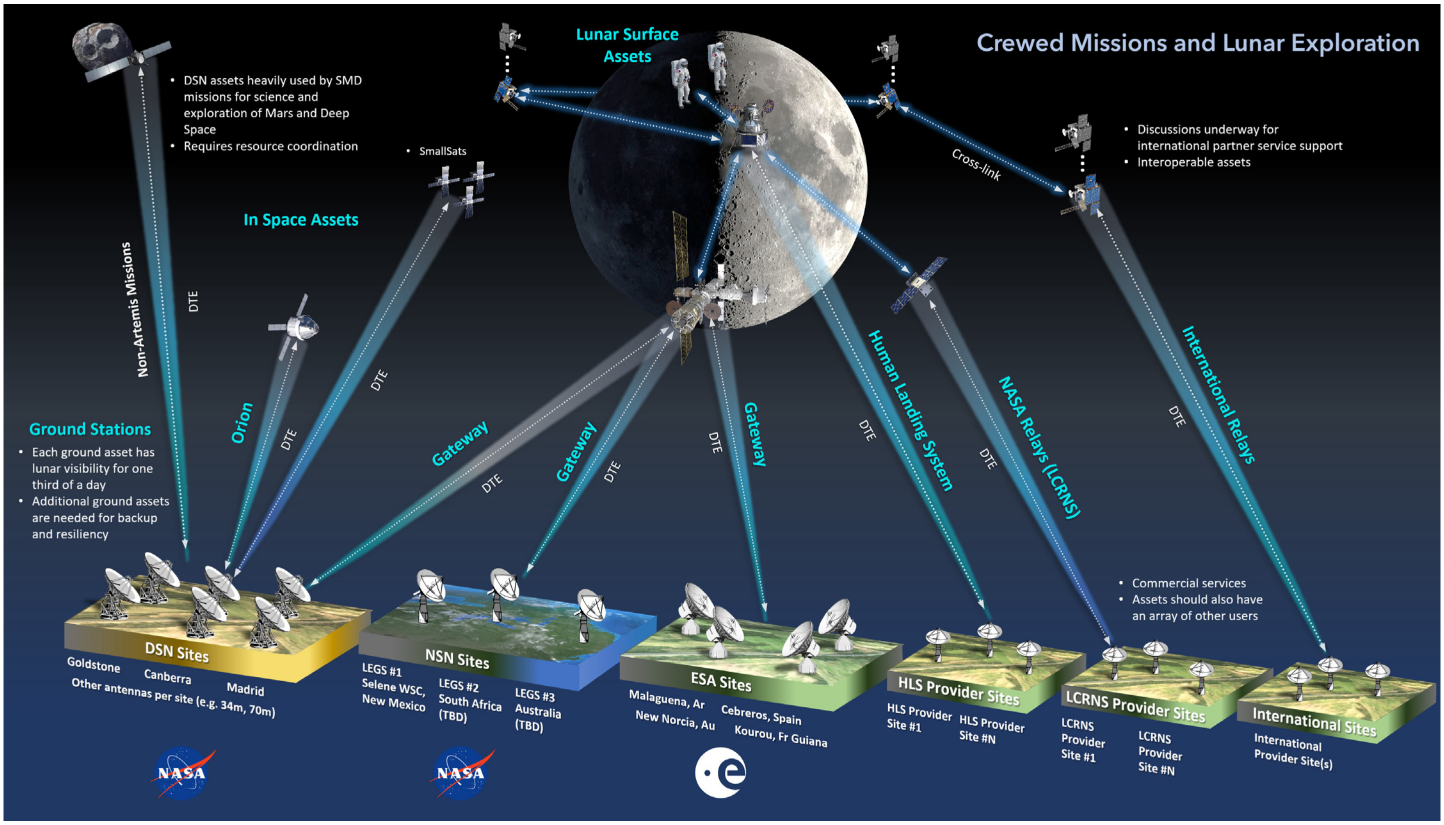

Figure 1. *The CPNT Architecture for Early Lunar Exploration*

A. Direct-to-Earth Communications

For users near the lunar South Pole, communications with Earth are complicated by the orbital geometry of the Earth-Moon system. The Moon's orbital inclination — the tilt of its orbit around Earth — and obliquity — the tilt of its rotational axis — cause Earth to be visible from the lunar South Pole for only about half of every sidereal month, the time it takes the Moon to orbit once around Earth (approximately 14 days). This will require deployment of orbiting relays to maintain continuous communications.

Furthermore, the topography of the polar regions is unlike the lunar maria, the large plains visited by the Apollo missions, or any region on Earth. For example, Shackleton Crater — a dominant feature of the lunar South Pole — is over two times deeper than the Grand Canyon. Nearby regions of interest are challenging for rovers and astronauts to traverse and safely navigate while maintaining reliable communications.

Additionally, when Earth is visible from the lunar South Pole, it is always seen near the Moon's horizon. The lunar terrain can also adversely affect communications signals traveling over it.[7]

Direct-to-Earth communications for Gateway and lunar missions will be supported by NASA's Deep Space Network facilities, NASA's Near Space Network's future Lunar Exploration Ground Systems, the European Space Agency's European Space Tracking (ESTRACK) network, and commercial ground assets. Together, these will provide near-continuous coverage to Gateway and the lunar South Pole when in Earth's view.

Projected communication needs beyond Human Lunar Return are expected to exceed the planned radio frequency communications capacity. Future optical communications capabilities, which use infrared lasers to provide higher data throughput, will accommodate the increased data volume at the Moon.

B. Orbiting Communication Relays

To close the gaps in direct-to-Earth communications, NASA is pursuing commercial satellite services to provide connectivity for missions on the lunar surface and in cislunar space. These providers will employ lunar-orbiting relay satellites with downlinks to commercial ground stations on Earth. Additionally, Gateway will provide communication links and limited PNT functions for surface and in-orbit users. International space agencies are also considering lunar communications relays, which may hold potential for collaboration.

The Lunar Communications Relay and Navigation Services project will provide consistent availability, visibility, and higher data rates for surface users. With multiple relays incrementally launched, the project can offer phased and incremental coverage of the South Pole region.[3] Early implementations will also offer preliminary PNT services as a stepping stone to a more robust, dedicated capability beyond the Human Lunar Return segment.

C. Surface Communications

NASA is pursuing trade studies on different approaches to lunar surface networking to select implementations that best meet the exploration requirements. These potential approaches include:

- Adapting NASA's Space-to-Space Communication System — a two-way communications system designed to provide voice and telemetry data between the space shuttle orbiter, the International Space Station, and the Extra Vehicular Activity Mobility Unit — at ultra-high frequency for voice communications.
- Using Wi-Fi for close-proximity high-rate video communications.
- Leveraging terrestrial wireless cellular standards for scalable, longer range, high-throughput connectivity with PNT services.[8] Such a network could enhance exploration range and mobility and the aggregation of data between a variety of science users.

Figure 2 illustrates the anticipated excursion ranges (e.g., a 2km extravehicular activity range) with different surface networking implementations, compared to exploration distances of Apollo 17.[9] Specific communications range distances can extend beyond those illustrated in the figure with varying data throughput. These ranges will also vary by system design choices and other considerations.

The combination of proposed approaches should meet exploration requirements. Range needs will vary by mission, driven by exploration objectives, crew mobility capabilities, and landing site considerations and constraints, such as terrain, slope, and regolith displacement due to landing.

During the Human Lunar Return segment, initial CPNT infrastructure concepts, capability, and hardware elements will be demonstrated through technology demonstrations and initial operational support. The expansion to longer term, sustainable implementation of a lunar surface network will occur during subsequent segments, incorporating advancements and lessons learned from technology demonstrations.

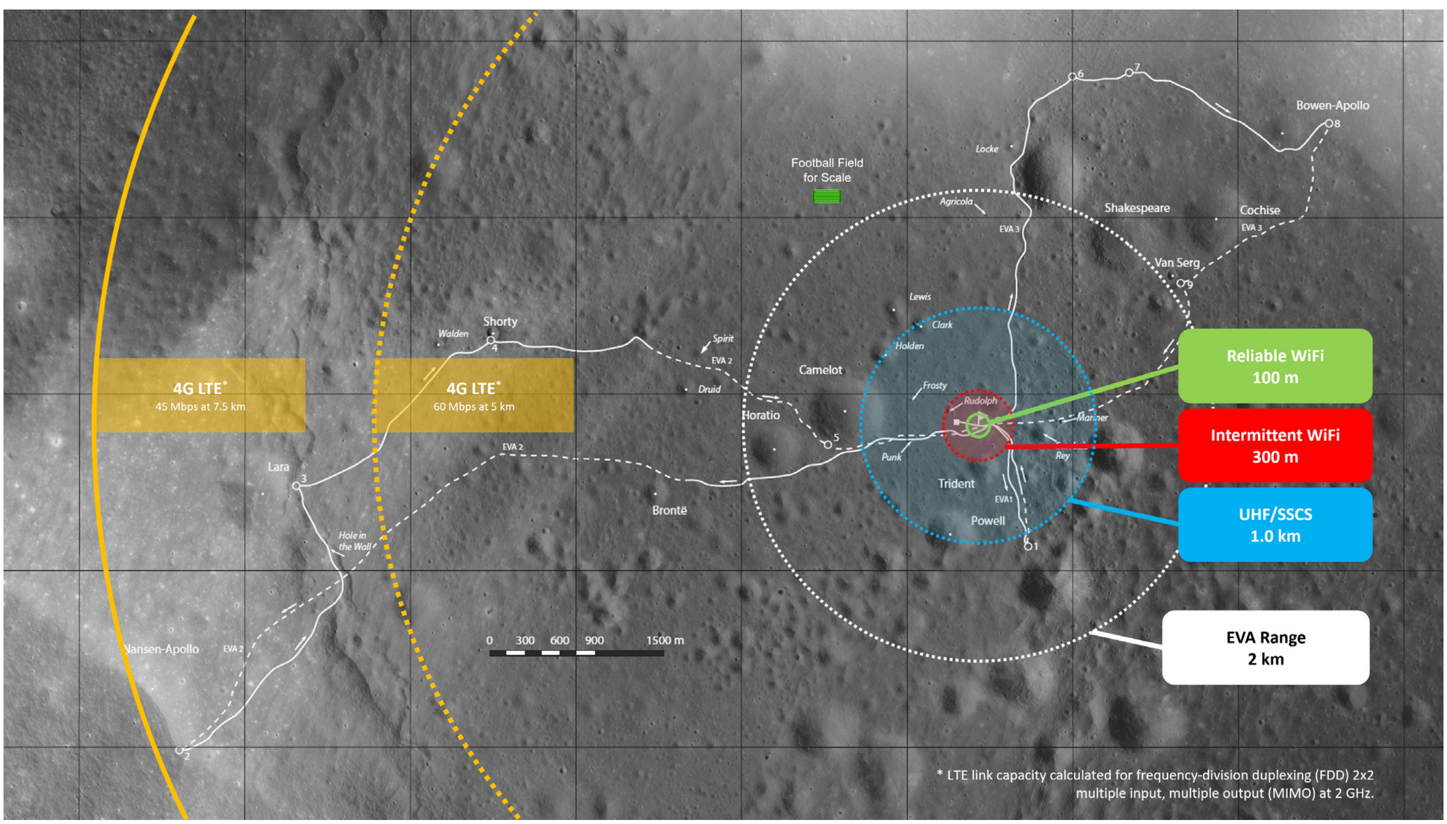

Figure 2. *A Comparison of Estimated Ranges for Several Surface Network Implementations, Plotted against the Longest Apollo-era Traverses with the Lunar Roving Vehicle during Apollo 17.*

III. Lunar Position, Navigation, and Timing Architecture

The lunar PNT architecture provides core functions to users on the Moon and in cislunar space. PNT capabilities allow lunar assets to know their current position, velocity, and time, and to navigate safely in lunar orbit and on the Moon's surface. Real-time, precise PNT services benefit the breadth of lunar users and scenarios, including orbiters, landers, surface exploration, and image and science collection. PNT needs vary from a Human Landing System accuracy requirement of within 100 meters of a planned landing site, surface position accuracy requirement of within 50 meters, and surface sample location marking accuracy requirement of within 10 meters.

There are a number of challenges associated with PNT on the lunar surface. Traditional methods of tracking by Earth networks will be difficult, if not impossible, during surface operations on the South Pole when users have limited or no line of sight to Earth. Use of GPS at the Moon is limited by the weakness of GPS signals at lunar distances, GPS satellite geometry, and occultation, where Earth blocks GPS signals from reaching the Moon. The variable lighting environment and challenging terrain conditions will make it difficult for the crew to use orienteering or camera-based approaches.

NASA's navigation architecture is comprised of both infrastructure and user capabilities. Infrastructure includes critical reference system components and radionavigation sources provided via communications and network assets. User-side capabilities include the onboard navigation systems that collect, process, and filter the data required to successfully navigate.

A. Infrastructure

Radio frequency (radiometric) sources are the most traditional means of navigation for spacecraft from near-Earth to deep space. At the Moon, these sources will include ground stations on Earth, satellites in orbit around Earth and the Moon, and assets on the lunar surface.

Earth-based Global Navigation Satellite System (GNSS) PNT services, like those provided by the U.S. Global Positioning System (GPS) constellation, can extend to the lunar regime in certain circumstances. These GNSS signals can aid the data diversity for resilient navigation when combined with traditional deep space signal tracking methods.

Communications relays in lunar orbit will provide cislunar and surface PNT services by broadcasting reference signals. One such approach, an augmented forward signal, combines navigation information with broadcast data messaging.

During the Human Lunar Return timeframe, NASA will roll out PNT capabilities across the early Artemis missions. This will begin with PNT provided by Earth-based tracking and surface elements, and expand to services provided by an initial relay satellite in luanr orbit. Subsequent to the Human Lunar Return segment, additional relay satellites could be supplied for a GNSS-like PNT capability that covers the global lunar service volume.

B. User Capabilities

In addition to using radiometric measurements from Earth, lunar orbit, and surface assets, lunar users will employ any number of other navigation data sources. These could include cameras and optical sensors, light detection and ranging (lidar) payloads, solar compasses, and inertial measurement units, which can use a combination of accelerometers, gyroscopes, and other tools to determine specific force, angular rate, and orientation.

During the Human Lunar Return phase, NASA will plan surface operations during well-illuminated conditions, allowing missions to rely largely on orienteering with use of maps, solar compass, and inertial measurement units. Additional sensors such as cameras or light beacons from a lunar lander will also be considered.

IV. Conclusion

The Moon to Mars CPNT sub-architecture defines the relevant functions necessary to achieve high availability, high throughput communications, and accurate PNT to enable the safe command and control of spacecraft, the return of science data, and precision maneuvering of assets. Together, these functions will enable the long-term goals laid out in NASA's Moon to Mars Objectives.

Through the Human Lunar Return segment, CPNT sub-architecture needs will be met through a combination of direct-to-Earth, space-based relay, surface-to-surface communications, navigation assets, and in-situ sensors. Deep Space Network facilities, upgraded to support additional Ka-band frequencies, and the Near Space Network's Lunar Exploration Ground Systems will provide near-continuous coverage of the lunar South Pole when in view from Earth and to Gateway. The European Space Agency's ESTRACK network will provide support for Gateway alongside potential commercial services from ground stations and lunar relay satellites, which could also support other cislunar and surface users.

Commercial and international partnerships will be key to developing a robust CPNT sub-architecture. During the Human Lunar Return segment, incremental improvements will facilitate more efficient network scheduling and utilization as a first step toward a more robust network management framework. These efforts are intended to meet the needs of near-term exploration and scale to support the increasing complexity of long-term lunar science and exploration.

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Lunar Logistics Drivers and Needs

Introduction

For human exploration missions, it is critical to provide items such as food, water, air, spare parts, and other similar products required to sustain life, maintain systems, and allow for productive science and utilization activities. Together, these types of goods are referred to as logistics items. This white paper breaks down the different types of logistics items, explains the mission and architecture drivers that determine logistics item needs, and identifies the types of logistics items that tend to dominate overall needs.

NASA has established a consistent process for developing initial estimates of logistics item needs for conceptual exploration missions. This process, which is based on previous spaceflight experience and input from technical experts, provides a comprehensive assessment of the logistics items needed to support exploration missions. Using a consistent process to estimate logistics item needs allows for proper assessment of logistics systems and consistent analysis of mission and architecture concepts.

The process for estimating logistics item needs for conceptual missions does not dictate requirements for future missions; formal logistics item needs for those missions will be determined based on detailed mission requirements. However, the process described here provides a comparable initial estimate of logistics item needs.

Composition of Logistics Items

Logistics items are all the equipment and supplies needed to support mission activities and are not part of a vehicle or element dry mass, with the exception of vehicle propellant and pressurants, which are not considered to be logistics items. Logistics items can be divided into the following categories:

Consumables: Includes all commodities that support the conduct of mission activities (often related to mission crew needs) that are not related to a specific payload or research activity. In some cases, this category also includes consumables driven by non-crew activities (e.g., air to account for air leakage and re-pressurizations). Examples of specific items include food, clothing, personal items, operational supplies, hygiene items, trash bags and other waste collection, towels, extravehicular activity consumables, and gases and liquids.

Maintenance items: Includes planned replacement hardware and associated tools for system components that have known limited lifetimes and have scheduled replacement plans. Planned maintenance needs are largely system dependent.

Spares: Includes spares and associated tools that address corrective maintenance for unexpected/unplanned failures of system hardware. The actual spares needs will depend on the system.

Utilization (payloads and research): Additional hardware and items (e.g., science, research, capability demonstration, outreach) that take advantage of the space-based architecture but are not required for crew or vehicle operations. For exploration mission planning, mass and volume allocations are typically defined rather than specific utilization hardware, as the latter often depends on specific mission objectives.

Outfitting: Subsystem hardware or components that are flown after the initial module delivery for permanent installation or use are defined as outfitting. As items are identified for outfitting, they are typically tracked as part of the integrated logistics plan. Outfitting often occurs when there are insufficient resources to implement all the desired functions within the initial launch mass or schedule, so key systems are delivered on alternate flights. Specific outfitting estimates depend on the mission.

Packaging, overhead, and carriers: Materials required to safely and effectively transport and store each of the logistics items. (This category does not include any spacecraft secondary structures required to house or contain logistics items).

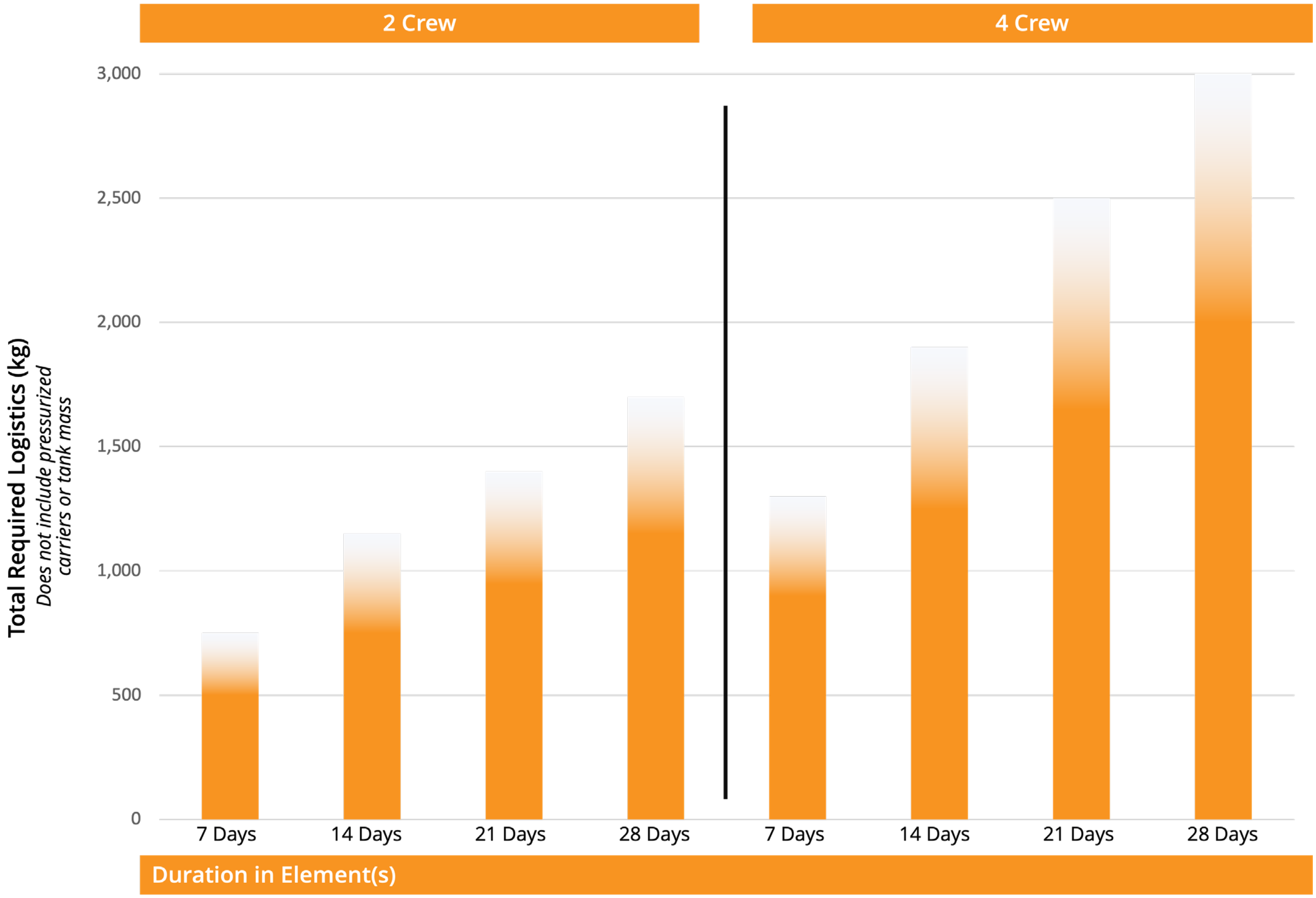

Figure 1. *Approximate Logistics Item Needs for Representative Lunar Surface Missions*

Lunar Logistics Drivers

Lunar mission logistics item needs are a function of the candidate mission and the proposed mission architecture. Although logistics item needs are determined by many factors, there are a few key contributors that have a predominant impact on overall logistics item needs. Typically, mission duration, crew size, environmental control and life support system (ECLSS) architecture, and extravehicular activity (EVA) cadence are the primary drivers. Mission crew size and mission duration are generally the most significant factors in determining the mass of logistics items. A large fraction of logistics item needs stems from crew support; these needs increase with the number of crew members and the mission duration.

The proposed ECLSS architecture is also an important consideration. An open-loop ECLSS, where waste products are not collected and recycled, will result in large needs for gas and water consumables. A regenerative ECLSS, where some waste products are recycled to produce water and gas, can significantly reduce or even eliminate gas and water resupply needs.

Crew EVAs on lunar missions can also be a significant driver of logistics item needs. EVA systems use significant amounts of water, oxygen, and other dry consumables. In addition, maintenance items, spares, and tools are required to maintain EVA systems. For missions with many planned EVAs, such as lunar surface missions, the overall EVA support mass can be a significant fraction of overall logistics item mass.

Logistics Item Estimates

Figure 1 shows approximate logistics item needs for representative lunar surface mission of varying crew sizes and mission durations. These estimates are for the mass of logistics items themselves and do not include carrier overhead mass. The uncertainty in the estimates shown in Figure 1 represents potential variability in mission operations and architecture. Changes in EVA cadence, ECLSS architecture, and element design can have substantial impacts on overall logistics item needs. While logistics item needs increase with crew size and mission duration, the increase is not linear, as certain fixed items are needed regardless of duration or crew size.

Figure 2 shows a representative breakdown by mass of logistics needs for a conceptual lunar surface mission with a significant planned cadence of EVAs. In this example, the habitation sub-architecture utilizes a fully open-loop ECLSS with no waste recycling. The water and gases needed to support the mission, including those for EVA, represent about half of the total logistics needs. Crew food and other crew consumables and EVA support items each represent about 20 percent of the overall needs. System maintenance and spare items and utilization items make up the remaining needs.

As missions progress to longer durations, spares and maintenance items can become larger drivers of overall logistics mass.

The ECLSS sub-architecture can have a significant impact on the overall distribution and total logistics item needs. With a high level of closure, the oxygen and water needs described in Figure 1, totaling almost 40 percent of overall needs, could be largely eliminated. However, regenerative ECLSS will generally increase subsystem mass and logistics item needs for maintenance and spares items.

The use of in-situ resource utilization capabilities can also have a substantial impact on logistics resupply. While in-situ resource utilization does not reduce the need for logistics items, it can reduce the need to deliver certain items, such as water and gas, to the exploration location.

Note that the mass of packaging, overhead, and carriers is not included in Figure 1. The bags, foam, and tanks that contain cargo items, as well as the pressurized carriers needed to deliver logistics to the lunar surface can add a large amount of overhead beyond the mass of the logistics items themselves. Based on historical performance, this added overhead could be between 75 percent and 150 percent of the base logistics item mass. However, the carrier mass depends heavily on the design of bags, tanks, and carriers.

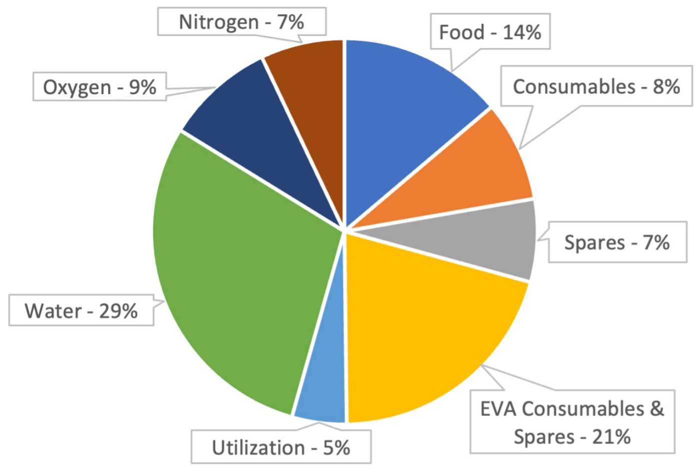

Figure 2. *Open-Loop Mass Breakdown Example*

Summary

As the exploration architecture is conceptualized and planned, it is imperative to accurately predict logistics resupply needs. The total amount of logistics items required to keep the crew alive and healthy, to maintain systems, and to perform productive science and utilization can be relatively large. It can also heavily influence the design of the architecture and exploration missions. The architecture must therefore be based on comprehensive, accurate estimates of logistics item needs and include assessment of a suitable logistics sub-architectures to deliver those needs.

Key Take-Aways

Logistics items are all equipment and supplies not initially delivered as part of a vehicle or element dry mass that are needed to support mission activities.

Crew size, mission duration, ECLSS sub-architecture capabilities, and planned EVA cadence are the primary drivers for the total logistics needs.

Water, gases, and food dominate overall logistics needs by mass.

The amount of logistics items that exploration missions require to keep the crew alive and healthy, to maintain systems, and to perform productive science and utilization is significant, and therefore it is important that the design and planning of the exploration architecture include comprehensive, accurate estimates of logistics item needs.

Lunar Site Selection

Introduction

Lunar site selection is an iterative process that evolves as we learn about vehicle capabilities, objectives, and architecture use cases and functions. Selecting sites for lunar operations requires identifying locations that would enable stakeholders to address one or more of NASA's Moon to Mars Objectives: in essence, "where we want to go," balanced with locations where safe lunar landings can be conducted, or "where we can go."

Available capabilities will evolve throughout the Moon to Mars Architecture segments, as defined in the Architecture Definition Document,[1] which will affect the relationship between "where we want to go" and "where we can go." As Artemis missions progress from the Human Lunar Return segment through Foundational Exploration and Sustained Lunar Evolution segments, mission planning will benefit from increased access to reusable infrastructure on the lunar surface and in orbit, as well as a better understanding of the lunar environment (for a detailed description of Moon to Mars exploration segments, refer to NASA's Architecture Definition Document).

Human Lunar Return missions will need to find safe landing locations close to the intended destination of surface operations as new systems are tested for the first time. Subsequent missions will benefit from the lessons learned during the Human Lunar Return segment, improving awareness of the lunar surface and environment and enabling more accurate landings, the ability to traverse longer distances across the Moon, and longer duration missions.

These improvements will relax the need for proximity between safe landing locations and intended targets of interest for surface science operations. As the architecture evolves, "where we want to go" will influence requirements for new systems, leading to an architecture that can reliably send astronauts to locations of interest.

Objectives Traceability

The Moon to Mars Objectives define the locations that NASA and its partners will need to access on the lunar surface or in lunar orbits in order to address our goals.[2] Therefore, traceability to these objectives determines "where we want to go."

Some objectives can be addressed simply through access to lunar orbits or the surface in general, without location-specific needs (e.g., observations of the human response to the lunar environment or gravity transitions). However, some objectives require access to specific environmental conditions or physical locations on the lunar surface, such as access to lunar volatiles in persistently or permanently shadowed regions or locations near multiple diverse terrain types, which would enable us to study the history of the Moon.

Progression through the architecture segments will likely result in an evolution of emphasis on different objectives. For instance, objectives that require longer stays and increased capabilities will benefit from favorable conditions, such as sustained access to greater-than-average amounts of sunlight to reduce thermal variability or to enable better power generation. As missions progress throughout the segments, NASA must achieve a balance between visiting previously unexplored terrain and developing routine and repeatable presence at select locations.

Lunar Conditions

Human Lunar Return activities will focus on conducting safe lunar landings and returning crews to Earth while conducting science in a region of the Moon that has not yet been explored by astronauts. These early Artemis missions will test new systems in new environments and establish a path for more capable missions to follow in later exploration segments. As these new systems are tested, the initial landings will need to identify relatively flat terrain, with only small blocks and impact craters that are within the lander's hazard tolerance. This type of terrain is also of value for initial extravehicular activities, or spacewalks, as the capabilities of new suits and surface tools are tested. Awareness of the physical characteristics of a potential landing site requires adequate data for site characterization. Each lander will have a unique tolerance for surface roughness or obstacle size; knowing if those obstacles are present requires proper data. NASA-acquired lunar data is made publicly available via the Planetary Data System[3] (the Lunar Reconnaissance Orbiter team provides a useful tool for accessing the data).[4] The highest resolution image data for the Moon has a resolution of roughly a single meter, but this resolution is not universally available across the polar regions. Therefore, data availability (data collected prior to or during a landing) and surface characteristics affect site selection.

Lunar lighting must also be taken into consideration; early landings will be conducted at times for which the landing site is largely sunlit throughout the entire mission. Therefore, the initial Human Lunar Return landing site should be sunlit for approximately 6–6.5 days. As the architecture continues to develop, access to sunlight will allow Artemis missions to use long-lived, reusable infrastructure to generate solar power, optimize systems to account for expected thermal extremes, and maintain hardware and crew within certain temperature ranges.

The Moon's low axial tilt results in polar lighting conditions that can range from areas of continuous darkness to areas that are often sunlit (however, there is no known location in the South Pole region that is continuously sunlit). Generally, higher topography terrain will experience a longer duration of access to sunlight. Furthermore, any hardware that provides additional height off the surface will increase sunlight access. The architecture can take advantage of this characteristic as it evolves.

Every location experiences a unique ratio or pattern of sunlight/darkness. These patterns can be predicted on the surface, but the ratio can vary significantly over short distances. Thus, the concept of a lunar day/night cycle at the poles is not consistent across the region and does not match our experience on the Earth, or even elsewhere on the Moon.

Identifying initial locations with favorable lighting can restrict landing access to limited time periods throughout the year, and there will be times when a landing cannot be performed because the region will be in shadow (Figure 1). Therefore, depending on when the mission launches, a desired landing site with gentle sloped terrain might not be in sunlight, and the period of darkness could be brief or extensive, lasting weeks or months. For a more detailed description of the lunar south polar lighting, refer to the 2022 Architecture Concept Review white paper "Why Artemis Will Focus on the Lunar South Polar Region."[5]

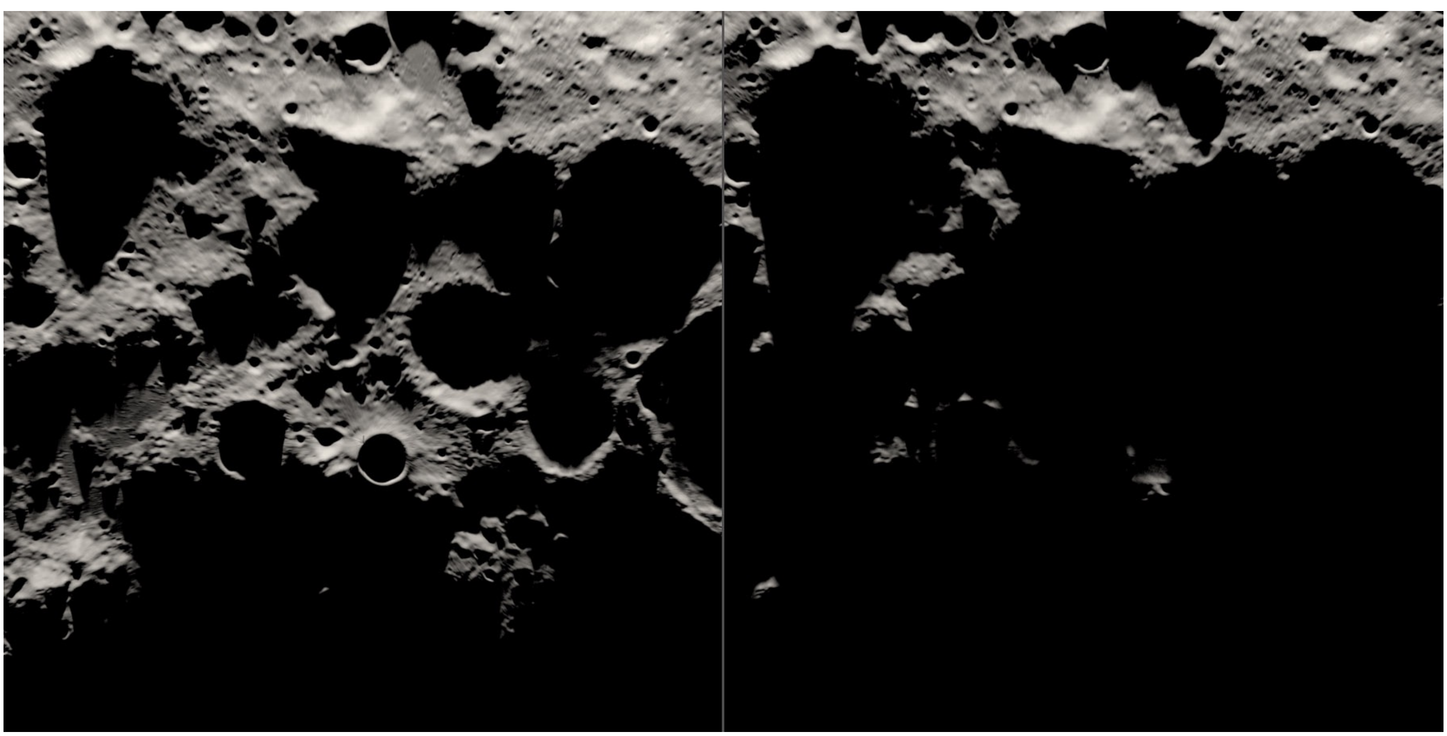

Figure 1. *Topographic maps of the lunar South Pole showing modeling lighting conditions during the summer season (left) and the winter season (right). Earth is to the top of the images. To see the full animated video of lighting conditions around the lunar south polar region please visit: [NASA SVS | Illumination at the Moon's South Pole, 2023 to 2030]*

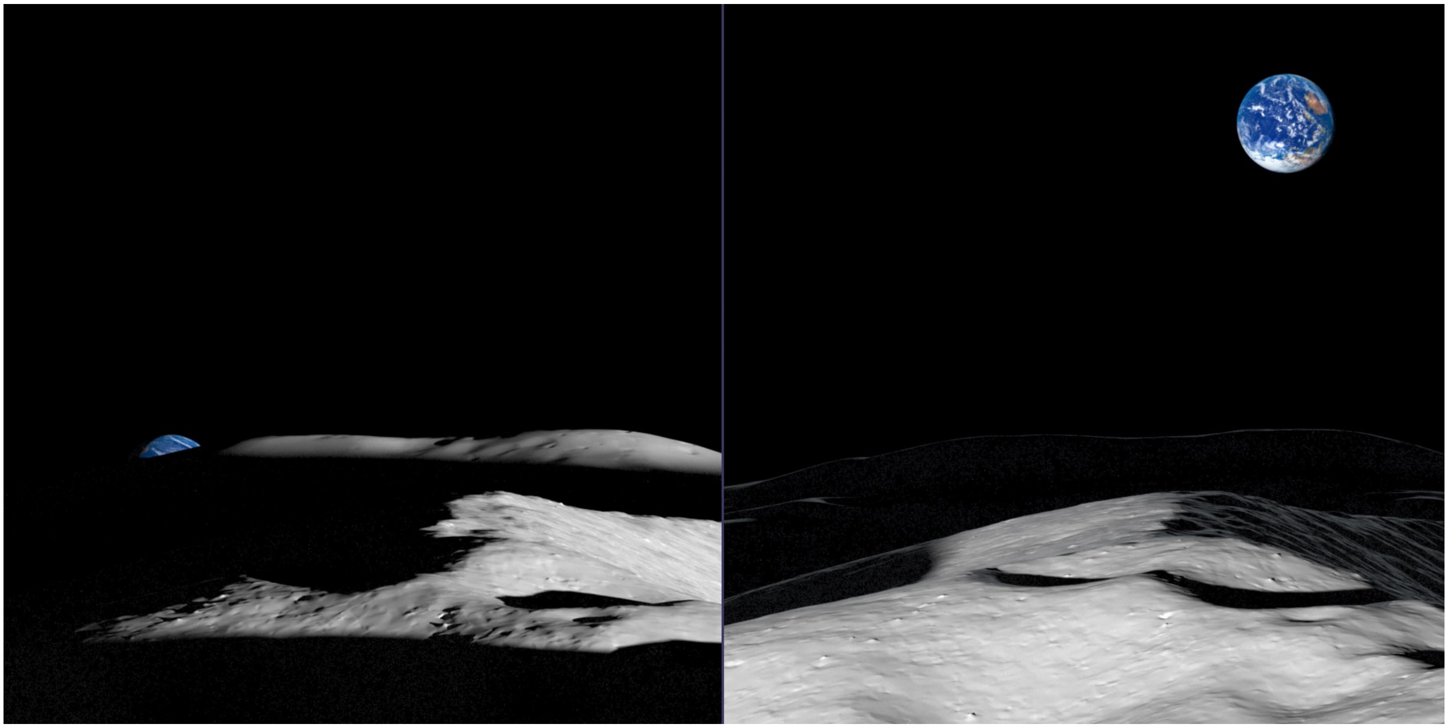

Figure 2. *Animations showing the same view of the Earth from a location near the South Pole. The degree to which the Earth is visible from this location changes over time, with the Earth being completely obscured at times throughout the year. To see the full animated video please visit: [NASA SVS | Earth and Sun from the Moon's South Pole]*

The lunar seasonal cycle does not overlap with Earth's seasonal cycle. The Moon will experience roughly 11 seasonal cycles per 10 Earth years. This means that over a decade, the alignment between lunar season and Earth season will shift. The lunar summer will slip against the Earth calendar over a series of years and the best months of lighting at the lunar South Pole will not be the same set of months on the Earth. Therefore, lighting at a given site will shift throughout the Earth year over time. Increasing capability to land in all lighting conditions will enable additional site opportunities.

Surface operations will require communications with personnel on the Earth. Prior to the establishment of communications infrastructure on or around the Moon, a Human Lunar Return landing site would likely need to depend on direct-to-Earth communications. This means that the Earth must be visible in the lunar sky from the landing site.

The Apollo missions landed on the Earth-facing side of the Moon, so the Earth was always visible in the lunar sky. However, the Earth is never visible from the far side of the Moon. The poles are located along the edge of the visible surface (disc) of the Moon as viewed from Earth, between the Earth-facing side and far side of the Moon (limbs of the Moon). Thus, much like lighting conditions, visibility of the Earth can vary (Figure 2).

The farther a location is past the pole toward the far side, the less likely the Earth is to be visible (and may only be visible from high-elevation terrain). Similarly, low-elevation terrain on the Earth-facing side of the Moon near the poles might also experience periods of time without direct Earth visibility. Additional architecture capabilities, such as communication relays, will enable more site selection options. As the exploration campaign progresses, surface mobility is likely to increase as well. As a result, planning for lighting and communications will not only need to account for landing, but also for traversing the lunar surface.

Mission planning will benefit from over five decades of lunar data collection. Although lunar conditions in the South Pole region are different from past Apollo experience, these conditions are repeatable and predictable. While no single location constantly — or even routinely — has ideal lighting and Earth visibility conditions, we can identify landing sites that are available over specific periods. As the architecture evolves through each exploration segment, lighting and communications considerations can be addressed to enable better access to locations of interest.

End-to-End Mission Availability

While the considerations above focus on the lunar surface environment, constraints, and operations, NASA assesses mission planning holistically. Building on lunar site conditions, developing end-to-end mission availability metrics requires incorporating when NASA's Exploration Ground Systems, Space Launch System (SLS), and Orion spacecraft can launch the crew to rendezvous with Gateway and/or the Human Landing System, which would be located in near-rectilinear halo orbit, to perform the lunar surface sortie.[6]

The Artemis enterprise's unique multi-vehicle, multi-launch architecture also creates additional ground processing challenges. For Artemis III, Orion will rendezvous directly with SpaceX's Starship Human Landing System. Rendezvousing with a prepositioned spacecraft creates additional constraints — mission planners must align the phasing of the target vehicle in lunar orbit with the window for Orion to intercept the Moon.

From an Exploration Ground Systems/SLS/Orion launch availability perspective, the vehicle configuration (SLS Block 1 or Block 1B) faces unique mission availability challenges. Artemis III will be the last flight of the Block 1 configuration. Artemis IV and beyond will use either the Block 1B or Block 2 configuration.

For SLS Block 1, the vehicle launches to an intermediate elliptical low-Earth orbit to best position the upper stage to perform the trans-lunar injection, placing Orion on a trajectory to intercept the Moon. Given the necessary launch geometry, Exploration Ground Systems/SLS/Orion can only achieve lunar orbit for roughly half of the Moon's orbit around Earth, nearly centered around the Moon's minimum lunar declination.

Orion's insertion into near-rectilinear halo orbit must also provide sufficient time for crew operations to prepare for the lunar surface mission. Thus, for Artemis III, mapping the intersection of available lunar landing sites with when the crew can launch and rendezvous with the Human Landing System is a critical component of mission availability.

Furthermore, once in near-rectilinear halo orbit, the Human Landing System is expected to be viable to conduct a lunar landing for about 90 days, meaning that the crew must arrive within that window of time to use the Human Landing System for a landing. Carrying multiple landing site options maximizes the likelihood of a successful landing across a calendar year within the multitude of mission constraints, one being the Human Landing System vehicle lifetime. In later segments of lunar exploration, the infrastructure could evolve to relax constraints on landing site availability and enable the selection of a single site.

For SLS Block 1B, the Exploration Upper Stage inserts into a circular low-Earth orbit. While this removes the performance constraint in the SLS Block 1 configuration, the new co-manifested payload capability can place additional performance demands on Orion. After the SLS Exploration Upper Stage performs the trans-lunar injection, Orion will be responsible for extracting the co-manifested payload and ferrying it to near-rectilinear halo orbit. The mass of that payload can significantly affect mission availability.

The mission designs for Artemis IV and beyond will also need to account for any timeline and consumable constraints. Mission availability for later Artemis missions will depend on the intersection of leveraging the range of the co-manifested payload capability and performing a lunar surface mission.

While this is a core component of near-rectilinear halo orbit accessibility, the later Artemis missions do benefit from the presence of Gateway and a lunar relay. The presence of these elements will help alleviate the challenges of direct-to-Earth communications for the Human Landing System and other future surface assets, ultimately opening additional lunar site availability.

In addition to all the nominal mission considerations above, protections for various contingency scenarios further restrict overall mission availability. The scope and coverage for these situations is a risk-informed decision that must maintain a delicate balance between the vehicle capabilities and protecting the crew.

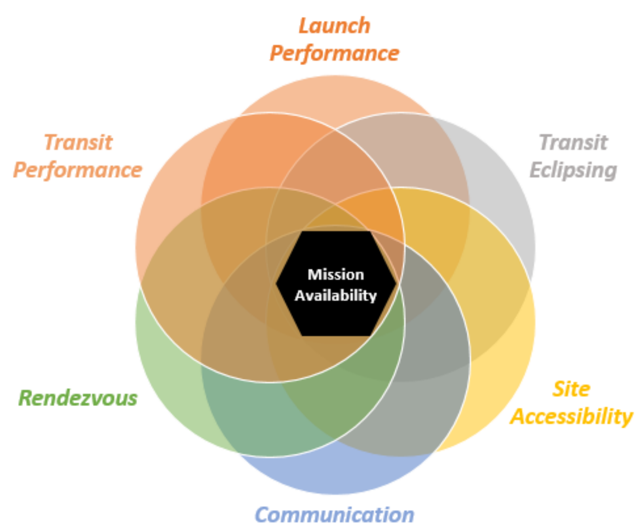

Figure 3. *Mission availability coordinates across multiple considerations, including vehicle capabilities and lunar environmental and physical characteristics. All of these factors must be considered when planning site selection for lunar surface operations.*

Site Selection Evolution

Lunar site selection considerations will evolve during the Foundational Exploration and Sustained Lunar Evolution segments. Both segments will involve an increase in capabilities to support lunar exploration from orbit and on the surface. Reusable hardware and surface infrastructure that can support longer stays and enable routine access to preferred locations and access to new locations will become key aspects of operations. Reusable surface assets are likely to be consolidated at one or more locations, which will have an impact on where we land, either to deliver new hardware or to use previously emplaced hardware.

As in the Human Lunar Return segment, the timing of a launch and landing can lead to different lighting and Earth visibility conditions from different locations across the south polar region. However, our approach to landings will evolve as our knowledge of the lunar environment and terrain characteristics increases.

For instance, the addition of communications capabilities will decrease the need for Earth visibility during landing or throughout a surface mission, and knowledge of the terrain and possible hazards for landers might lead to landing options in regions that are partially or entirely dark.

As infrastructure is emplaced on the lunar surface, subsequent landings might need to be conducted at or around the same locations multiple times, meaning that site selection drives the mission. Returning to the same location will require relaxation of site accessibility constraints related to lighting, communications, and terrain awareness, which could be addressed through continued data acquisition for that location and contributions from the evolving architecture.

New landing site characteristics might need to be considered. Hardware that remains on the surface could become an obstacle to future landings and surface operations; if that hardware remains in use, future landings will need to account for the plume surface interactions that landers create during descent and ascent. Furthermore, deployed hardware could become an obstacle for sun visibility for previously deployed elements.

All partners operating on and around the Moon will need to consider these factors. As the architecture develops, it should use reusable infrastructure to relax some landing site constraints, thereby enabling mission planners to access locations of interest more dependably as missions progress. However, permanent infrastructure will also introduce important new considerations.

Summary

Identifying lunar sites for landing and surface operations is an iterative process that considers vehicle capabilities, objectives, and architecture use cases and functions. Any mission must balance "where we want to go" with "where we can go" safely with our crew and other assets based on the capabilities available at that time. Site selection must account for characteristics such as surface roughness and slope, lighting, and, in early missions, visibility of the Earth. Mission planners require lunar data about these characteristics to match with vehicle capabilities.

We must also consider the performance of multiple vehicles to enable spacecraft to reach Earth orbit, initiate the trans-lunar cruise, rendezvous with other previously deployed spacecraft in lunar orbit, and begin the descent to the lunar surface. Before we establish surface and orbital infrastructure to support these activities, early landing locations will be heavily influenced by when the crew launches from the Earth (Figure 3). As supporting infrastructure is emplaced and we learn about operations in the lunar south polar environment, mission planners will use the additional information to consider a broader range of sites to meet NASA's Moon to Mars Objectives.

Key Take-Aways

Physical and environmental lunar conditions will have a strong influence on site selection, including surface roughness and slope, lighting, and Earth visibility.

Coupled with vehicle capabilities, the early Human Lunar Return mission sites will largely depend on when the crew launches.

As supporting infrastructure is emplaced over time through the Foundational Exploration and Sustained Lunar Evolution segments, accessibility to sites of interest should increase and establish a stronger link to NASA's Moon to Mars Objectives.

References

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Safe and Precise Landing at Lunar Sites

I. Introduction

The Artemis missions will land astronauts on the lunar surface to leverage the unmatched capabilities of human explorers. These landings will commence long-term exploration and utilization of the Moon by NASA, industry, and international partners for the benefit of all.

With humanity's impending return to the lunar surface, precision landing of human spacecraft on the Moon's surface is a fundamental challenge. The ability to land in proximity to the specific sites with demonstrated value for exploration, commerce, and science will be critical to achieving our Moon to Mars Objectives. Precision landings will enable spacecraft to avoid hazardous features, promote crew safety, co-locate infrastructure, and increase science and exploration returns.

This paper introduces the mechanics of and methodologies for precision lunar landing and explains critical aspects of landing, including vehicle navigation capabilities, plume-surface interactions, geospatial considerations, and science-related needs.

2. Safe and Precise Landing: What Does it Mean?

Precision landing generally refers to the process of navigating a spacecraft to a safe landing location in close proximity to a specified target. For example, a precision landing could be qualified as a requirement to safely touch down within 50 to 100 meters of a given target on the lunar surface.

Precision landing is often coupled with hazard avoidance, resulting in the term "precision landing and hazard avoidance" (PL&HA). Implementing PL&HA systems on a spacecraft enables the landing of multiple assets within a targeted surface region or landing zone while avoiding collisions and limiting damage to existing surface assets. This mitigates the risk of unsafe touchdown for new landers and reduces post-landing travel distances between surface assets.

Literature on PL&HA often conflates precision landing to also imply safe and/or accurate landing. While both precision and accuracy are measurements of error in landing, precision is the measurement of how close landings are to one another, whereas accuracy is a measurement of how close they are to their intended target.

Both accuracy (offset error from truth) and precision (uncertainty of the offset) are crucial for ensuring successful lunar missions, as they allow scientists and engineers to select specific landing sites of interest that better meet science or resource exploration objectives. For the remainder of this paper, the terms "precision landing" and "PL&HA" will be synonymous with safe, precise, and accurate landing.

3. Science Purpose and Needs

Landing at precise locations will help NASA meet lunar science objectives by guiding explorers closer to scientifically rewarding areas on the lunar surface. The Apollo Program demonstrated that landing human explorers near specific geologic features dramatically improves science return. The Apollo missions resulted in paradigm-shifting science discoveries that transformed our understanding of the Universe.

Proximity increases efficiency, effectively utilizing precious crew time and enhancing the quality and accuracy of data collection. That improvement in data collection enables researchers to gain deeper insights into the Moon's history, composition, and geology.

With the limited duration of extravehicular activities, landing in regions that meet illumination and communications requirements and optimizing proximity to areas of scientific interest will be critical to returning precious lunar samples to Earth for further analysis. Furthermore, precision landing near resource- and volatile-rich zones will help us understand and utilize the Moon's resources.

In addition, coupling precision landing with a hazard detection and avoidance system enables the lander to more accurately maneuver clear of hazardous obstacles. An effective PL&HA system could select landing sites with more benign surface conditions to improve lander touchdown stability.

Such a system could also offer mitigation strategies for plume-surface interactions (PSI), where the exhaust from a lander kicks up lunar dust, or regolith. This could help minimize the hazard that ejected regolith poses to surface assets and prevent contamination of scientific areas of interest.

4. Surface Architecture

Precision landing can enable aggregation of surface assets in closer proximity, improving efficiency and risk posture. Whether using robotics or crew members to transfer logistics items, a reduction in distance means a reduction in transfer time and risk.

As an example, landing a logistics module closer to a habitat module would ease the transfer of items from one module to the other. Keeping assets within extravehicular activity walking distances or within rover mobility distances enables efficiency of time spent on science and utilization.

As the number of government and commercial landers on the surface increases, there will be a critical need to ensure that associated keep-out zones are respected. Precision landing capabilities can help achieve this. Additionally, knowing the final, accurate location of the landed asset will enable planning for landing additional assets.

While enabling co-location of surface assets can be beneficial, there are also potential risks. The larger the engine, the higher the potential for PSI events that could damage existing surface assets. There is little lunar atmosphere to slow PSI ejecta during landing, and lunar regolith is essentially shrapnel from meteors impacting the surface without the weathering that takes place on Mars or Earth. While precision landing and close asset aggregation reduce transit times, surface assets will have to mitigate against PSI ejecta, which may require asset hardening.

5. Navigation Capabilities

Consider a typical lunar deorbit, descent, and landing trajectory. A deorbit burn inserts the lander from a low lunar orbit to a transfer orbit with a low periapsis (e.g., 15–20 kilometers). Powered descent initiation occurs at or near periapsis and begins with a braking phase designed to reduce lander velocity as efficiently as possible.

During powered descent, the lander transitions to an approach phase where attitude and altitude ranges permit the use of landing sensors and pilot visual contact with the landing site. At the end of the approach phase, the vehicle is directly above the target landing site and terminal descent begins, with the lander approaching the lunar surface until touchdown.

Throughout these phases, the onboard navigation system must provide accurate and precise estimates of lander position, velocity, and attitude so that the guidance and control algorithms can plan and execute maneuvers that deliver the vehicle to a safe touchdown in close proximity to the target site.

Navigation systems can include an assortment of components: software algorithms, onboard sensors, celestial navigation tools, maps of terrain features, and other devices for external measurements. Over the years, NASA has performed numerous studies and developed many relevant technologies[1] for precision landing through projects such as Autonomous Landing and Hazard Avoidance Technology (ALHAT)[2] and Safe and Precise Landing – Integrated Capabilities Evolution (SPLICE).[3]

The ongoing SPLICE project has been tasked with advancing the technology readiness levels of key deorbit, descent, and landing guidance, navigation, and control systems. The project is also implementing simulation tools for conducting navigation sensitivity and performance studies for autonomous precision landing.

Findings from focal SPLICE navigation studies[4,5] demonstrate how improved physics-based engineering simulations and modeling fidelity can enable rapid, detailed assessments of the integrated performance of these systems. These simulation tools can evaluate the effectiveness of different navigation sensors on overall

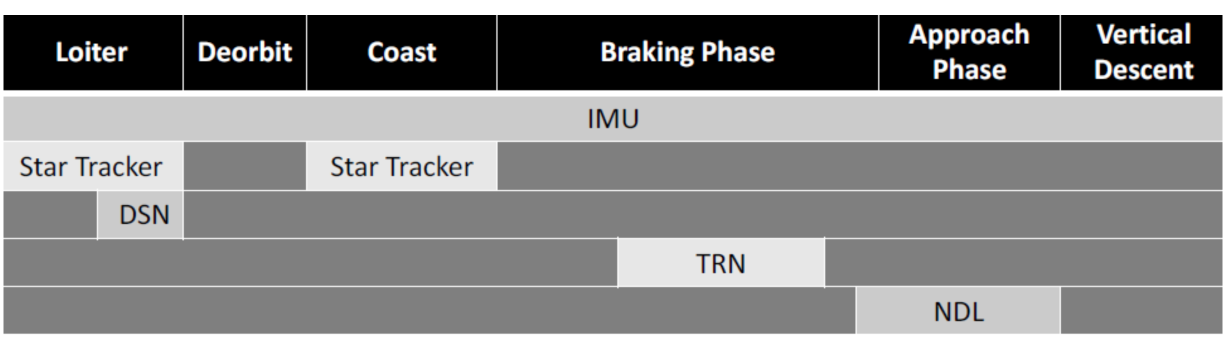

Figure 1. *: Sensor Assumptions Modeled from Lunar Orbit to Vertical Descent [2]. Acronyms: DSN (Deep Space Network), NDL (Navigation Doppler Lidar) velocimeter, TRN (Terrain Relative Navigation), IMU (Inertial Measurement Unit)*

system performance. Sensors that can be integrated into these analyses include an array of inertial and relative sensors on which navigation systems would rely, such as accelerometers, gyroscopes, star trackers, altimeters, velocimeters, terrain relative navigation systems, and hazard detection systems. Figure 1 shows active sensors during particular deorbit, descent, and landing phases in an example scenario.

Powered descent is a short-duration event (approximately 10 minutes). Utilizing Earth-based ground tracking updates for vehicle navigation during powered descent is not feasible due to the turnaround time required to process Earth-based tracking measurements and then communicate them up to the spacecraft. Instead, this phase relies on a lander's onboard sensors.

Terrain relative navigation matches real-time observations of the lunar surface (e.g., camera images for passive navigation and lidar/radar surface contours for active navigation) to pre-flight maps stored onboard. Terrain relative navigation capabilities can improve lander state knowledge from the initial deorbit and braking burns.

Onboard maps are derived from orbital reconnaissance imaging and digital elevation models generated prior to a mission. Verification and validation of these pre-flight maps are critical to the success of terrain relative navigation. Passive approaches utilize cameras that require surface illumination from the Sun, as well as surface maps obtained or rendered with similar illumination conditions. Active approaches utilize a sensor like lidar or radar that do not require solar surface illumination for imaging; this approach obtains contour maps during descent that are then matched against onboard digital elevation models.

Additional architecture systems such as orbital communications relays, Global Navigation Satellite System (GNSS) signals, ground references, or surface beacons can also help support navigation capabilities for precision landing.[6,7]

6. Geospatial Aspects and Hazard Detection & Avoidance

The lack of an Earth-like atmosphere on the Moon means that even small meteorites impact the surface. This results in regolith heavily covered with impact craters and ejecta of varying sizes. These impact craters, ejecta, and other surface features (e.g., exposed uneven bedrock) present hazards to landers, which typically will have some maximum hazard size and surface slope that can be accommodated by landing systems (e.g., landing gear/mechanisms, footpads).

Lunar surface geospatial data and analysis play a pivotal role in mitigating these hazards. Coordinated data fusion of relevant planetary mission datasets enables detailed evaluation of candidate landing sites. Mapping increases the likelihood that a safe landing can occur in a given surface region.

These analyses examine data to assess terrain types, identify hazards, and evaluate surface illumination conditions. Current knowledge of surface features based on direct observations at proposed Artemis landing sites remains at the scale of meters per pixel. High-resolution mapping techniques such as shape-from-shading[8] may be used to enhance imagery and improve landing site characterization for hazard avoidance planning.

Every lander has engineering constraints related to the size and characteristics of potential hazards that can be overcome during a safe landing. Given enough data from landing site observations and lander capabilities, an informed trade between pursuing further site knowledge versus investing in further lander robustness can be made.

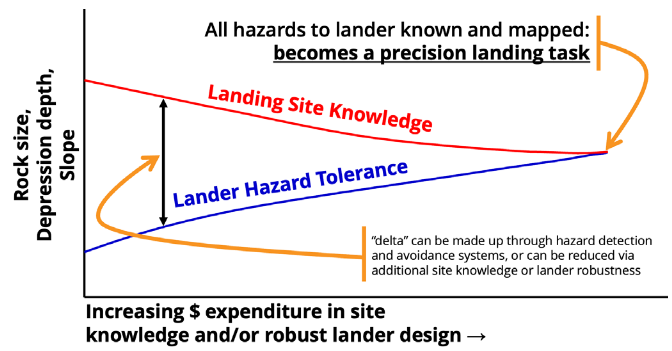

Figure 2. *Site Knowledge vs. Lander Tolerance Continuum*[7]

The trades between lander robustness — a local hazard accommodation size for a given lander — versus site knowledge — the available resolution of features and hazards at a desired landing site — can be summarized as follows:

1. Improved hazard size accommodation by the lander (e.g., through a landing gear redesign)
2. Improved orbital mapping resolution of the desired landing site to identify smaller hazards (e.g., through better or increased orbital observations of the area)
3. Implementation of an onboard hazard detection and avoidance system

The first two options are often constrained by program resources, schedule, and vehicle margins (e.g., maximum size and mass of the lander given launch vehicle constraints or remaining propellant onboard a lunar orbiter for obtaining closer images of targeted landing regions). The third option may be relatively lower cost since it does not require a vehicle redesign or additional mapping from orbiting assets.

A balanced mix of all three options will aid in achieving NASA's Moon to Mars Objectives. Observations by NASA's Lunar Reconnaissance Orbiter and other missions have characterized the lunar surface environment very well. These data can inform hardware design choices quantitatively.

NASA has identified a need for a continuous lunar observation capability to preserve and enhance Lunar Reconnaissance Orbiter capabilities. These would be provided through follow-on NASA and/or commercial missions, enabling continued surface situational awareness for planned lunar activities. In addition, international partner missions are collecting valuable datasets that can be leveraged as more nations conduct lunar surface observations.

Hazard detection and avoidance systems can be passive or active, consisting of either:

1. An optical camera able to passively image illuminated localized hazards and indirectly detect them via shadow detection and feature identification algorithms.
2. A lidar able to actively image illuminated, shadowed, or unlighted hazards and directly detect them from point-cloud range data. An onboard hazard avoidance system would use this information to determine a safe landing location within lander performance margins.

Hazard detection may also be coupled with terrain relative navigation systems, either by sharing imaging hardware or through software algorithms.

The needed capability to process orbital lunar surface data to a resolution that provides adequate pre-mission hazard mapping varies by location on the Moon. Some regions will require a lander to have a higher hazard tolerance or higher hazard avoidance capability than others — even with tightly resolved features — due to the size of the hazardous features on the surface. The Moon to Mars Lunar Surface Data Book [9] describes the process to resolve features, assumptions made, and modeling analyses.

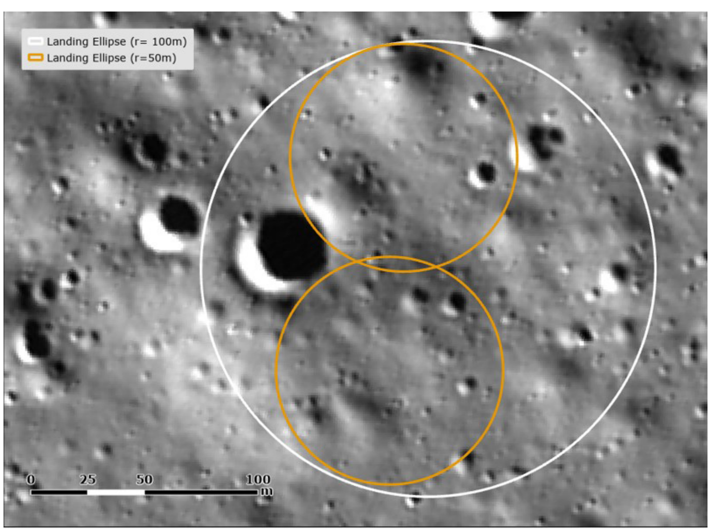

Figure 2. *: r=100m Landing Ellipse vs. r=50m Landing Ellipse (Artemis Geospatial Data Team)*

With the variability of surface crater and hazard size and distribution on the lunar surface, geospatial analyses generally focus on identifying zones with relatively safe landing conditions. In general, greater precision landing capabilities enable access to more surface sites, since smaller areas can be assessed to determine if hazards are present.

Figure 3 includes an example of hazard avoidance by reducing the radius from 100 meters to 50 meters. In the image, the 100-meter-radius ellipse contains one large crater with potentially unsafe landing conditions. However, the 50-meter-radius ellipses can remain safely outside the large crater while still allowing a close enough distance for trips to the crater region, if desired.

7. Plume-Surface Interaction (PSI)

PSI results from rocket engine exhaust interacting with a planetary surface during descent, landing, or ascent.

The Apollo missions experienced regolith ejections that obscured views of the landing site during final approach and touchdown. Apollo 12 sandblasted the Surveyor 3 lander located 155 meters away. Apollo 15 landed on a crater slope, very nearly violating the tilt limit for safe ascent and sustaining structural damage to its descent engine bell, which would mean not being able to re-use that engine for ascent.

The Mars Science Laboratory eroded significant craters with its Skycrane engines. Mars 2020 Perseverance's descent and landing footage showed high-velocity debris and dust that completely obscured the cameras during touchdown. Both the Mars Science Laboratory and Perseverance showed evidence of debris impact damage.

These past missions indicate that PSI can impact safe, precise landings and negatively affect landing sensor performance. Potential risks from PSI vary with lander configuration, concept of operations, and landing site. Many new lunar lander designs use the same vehicle to descend to the surface and later ascend back to orbit (i.e., single-stage) and are significantly larger in size than those flown by Apollo. They also have very different operations, which could result in a very different induced-hazard potential from Apollo.

NASA currently lacks direct in-situ measurements of PSI phenomena, leaving predictions largely qualitative and uncertain. Validation and model improvements require ground testing and in-situ data.

NASA has conducted small-scale vacuum tests with different types of simulated regolith and plans to conduct more complex testing in the coming years to reducing PSI risk for the Human Landing System. The tests would allow the agency to improve models that currently rely on Apollo flight reconstructions.

In addition, upcoming Commercial Lunar Payload Services missions aim to capture PSI data using stereo cameras. These cameras will image the area under the landers during descent and touchdown.

These observations represent a first step in understanding ejecta size and velocity on the lunar surface, which will be crucial to understanding surface asset proximity limitations, what risks exist, and how to mitigate those risks. Various technology efforts are planned or underway across NASA, industry, academia, and international partners for PSI testing, in-situ sensor development, and modeling advancements.

8. Conclusion

Precision lunar landings have become increasingly important as space agencies and private companies aim to establish a robust, long-term presence at the Moon. Though there are many technical challenges to overcome, precision landings represent a pivotal advancement in space exploration technology. The potential benefits include enhanced safety for crewed missions, optimal targeting of scientifically valuable sites, and minimizing site contamination risks. Precision lunar landings will empower scientists to better study specific geological features, conduct experiments, analyze lunar soil, and gather valuable data about the Moon's composition, history, and potential for future human exploration or resource utilization.

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Analytical Capabilities In Situ Versus Mass of Returned Lunar Samples

Introduction

The emerging capabilities of NASA and its commercial and international partners to land significant payloads on the surface of the Moon will provide opportunities to land large and diverse suites of science instruments. It will also provide opportunities to return samples to Earth for scientific analyses in Earth-based laboratories.

During the Apollo Program, the return of samples to Earth was the only viable way to obtain accurate and precise mineralogical and geochemical analyses of lunar samples; technology was simply not available or mature enough to enable these detailed scientific investigations in situ. As mission capabilities improve, architecture is refined, and analytical technologies improve with NASA's return to the Moon with the Artemis missions, a question arises:

Can modern payloads to the Moon provide sufficient analytical capabilities to replace the need for return of samples to Earth?

This paper provides a brief overview of the science enabled both by conducting analyses in situ on the lunar surface and by returning lunar samples to Earth. Several examples illustrate how both in-situ and returned sample analyses can address the lunar/planetary science (LPS) goals of the Moon to Mars Objectives.

These examples represent only a snapshot of the extensive breadth and depth of LPS and other lunar surface sample-dependent objectives. Other lunar science objectives facilitated by geophysical instruments (e.g., seismometers, heat probes, magnetometers, laser reflectometers), which by their nature require in-situ analyses, are not discussed in the context of in-situ analyses versus mass of returned samples. However, sample return may provide supplementary context for interpretation of those geophysical results.

The question of in-situ analyses versus mass of returned samples needs to be addressed on a case-by-case basis for each science goal. The strengths and weaknesses of each approach mean they are rarely directly interchangeable, and this variability should be taken into consideration during architecture definition. Broad Artemis and Moon to Mars goals will best be achieved by an integrated strategy that uses both sample return and in-situ measurements.

Lunar/Planetary Science Objectives

Goal: Address high priority planetary science questions that are best accomplished by on-site human explorers on and around the Moon and Mars, aided by surface and orbiting robotic systems.

LPS-1: Uncover the record of solar system origin and early history, by determining how and when planetary bodies formed and differentiated, characterizing the impact chronology of the inner solar system as recorded on the Moon and Mars, and characterize how impact rates in the inner solar system have changed over time as recorded on the Moon and Mars.

LPS-2: Advance understanding of the geologic processes that affect planetary bodies by determining the interior structures, characterizing the magmatic histories, characterizing ancient, modern, and evolution of atmospheres/exospheres, and investigating how active processes modify the surfaces of the Moon and Mars.

LPS-3: Reveal inner solar system volatile origin and delivery processes by determining the age, origin, distribution, abundance, composition, transport, and sequestration of lunar and Martian volatiles.

LPS-4: Advance understanding of the origin of life in the solar system by identifying where and when potentially habitable environments exist(ed), what processes led to their formation, how planetary environments and habitable conditions have co-evolved over time, and whether there is evidence of past or present life in the solar system beyond Earth.

Lunar Samples as Unique But Complex Records

The Moon serves as a historical archive for the Earth and inner solar system, recording events that happened billions of years ago.

Geological processes on Earth — such as plate tectonics and erosion by wind and rain — have erased all but a few rocks from the first billion years of Earth's history. By contrast, the Moon lacks major ongoing geological activity, with the exception of surface modification by impact events and space weathering. The Moon's major structural characteristics, including core formation, crustal formation, and the freezing of the interior structure, were largely established about 4 billion years ago, with major volcanic events complete by about 3 billion years ago.

Samples of the Moon therefore preserve unique records of the most ancient history of the Earth-Moon system and of the inner solar system (including Mars). Fundamental science achieved through analysis of lunar samples includes, but is far from limited to:

- Understanding the evolution of rocky planetary bodies.
- Establishing absolute ages of cratered surfaces throughout the solar system.
- Understanding the space weathering of airless bodies in the solar system.
- Constraints on the formation locations and later adjustments in orbits of the gas giants.
- Improved understanding of our solar system's history as it revolved around the Milky Way galaxy.

Lunar samples also provide information regarding the origin and evolution of volatiles on the Moon and Mars, with implications for both in-situ resource utilization and science.

While documents such as the Artemis III Science Definition Report and the Moon to Mars Objectives (e.g., LPS 1–4) capture many major science goals, the scope of science achievable through lunar (and Mars) sample analyses is vast. This is especially true for returned samples, which can be studied with ever-improving instrumentation to address new science questions for many decades after the completion of the original mission.

Unlocking the events and processes recorded by lunar samples includes a significant challenge: the history preserved in each rock is extremely complex. Unravelling this complexity requires detailed knowledge of the samples' origins and locations, careful preparation of samples, detailed sample characterization, and many types of analyses with high accuracy, high precision, and high spatial resolution. Obtaining this knowledge will require many specialized types of analytical techniques and instruments.

Prerequisites for Analysis: Finding and Preparing the Right Material for Analysis

Lunar samples are chemically and mineralogically diverse (Figure 1), as demonstrated by the many different types of rocks collected during each Apollo mission, as well as the overall diversity of the Apollo sample collection. Much of this diversity was captured because of the relatively large mass returned and the multiple, geologically different sampling locations.

Even with more than 2,200 individual samples totaling 382 kg, many types of samples were only represented by a few grams of material or just a single sample (e.g., green and orange volcanic glass beads from Apollo 15 and 17, respectively; troctolite from Apollo 17, from deep in the Moon's crust; anorthosite from Apollo 15 [Genesis rock]), and many more sample types were likely unaccounted for in the collection. Addressing the breadth of science questions encompassed by the Moon to Mars Objectives requires analyses of many different types of samples present within a given terrain, which can be collected either by crewed extravehicular activity or uncrewed rovers.

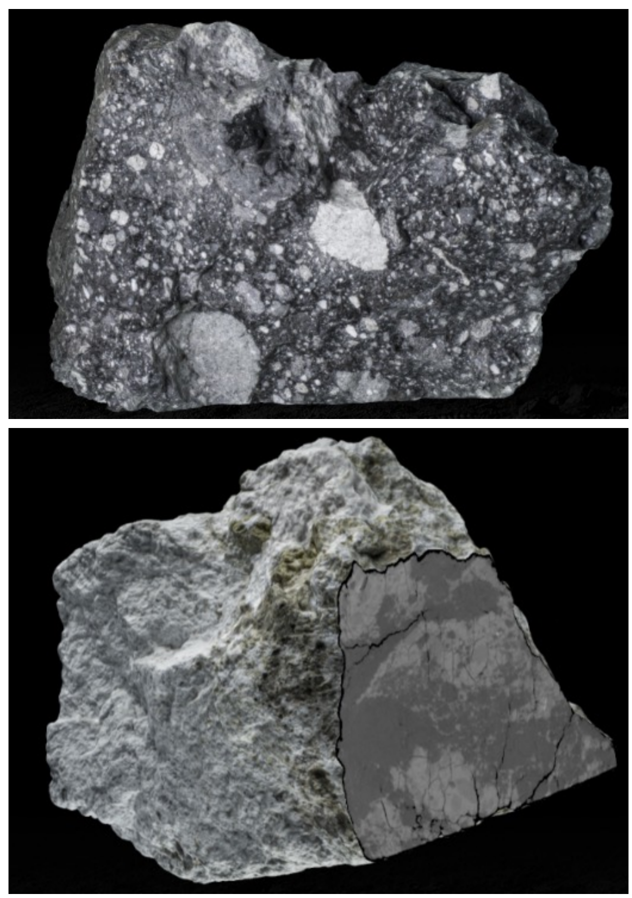


Figure 1. *Apollo sample 60019 (top) is a breccia with distinct light and dark clasts. Other samples, such as 60025 (bottom) appear more uniform at the surface but overlaid X-ray imaging of the interior (lower right portion of the sample) reveals pervasive heterogeneity. Both samples were collected during Apollo 16. (Images from NASA's Astromaterials 3D project).*

Achieving science goals requires analyses not just of these representative bulk samples but of the many pieces that make up each rock — individual minerals, grains, clasts, etc. Each rock is like a puzzle with hundreds of pieces, and each piece, or sub-sample, sheds light on a different part of the story.

Sub-sample components can record distinct and specific processes — for example, zircon is a key mineral for chronology (LPS-1), apatite and other minerals retain volatiles from magmatic/volcanic processes (LPS-2), glasses and agglutinates can record surface processes (LPS-1, 3), and rare dunitic and granitic clasts record a much broader range of magmatic and volcanic events than basalt alone (LPS-2). Exploring the lunar South Pole region and associated permanently shadowed regions will require analyses of regolith, rocks, and ices of different origins, which were deposited and sequestered by different natural mechanisms throughout the Moon's history (LPS-3).

In-situ analyses –
Collection of samples is best conducted in concert with broader surface geological investigations, such as by trained crew and/or with in-situ instruments. Together, these provide better context for the site from which a sample is collected.

Geologic context is crucial for the correct interpretation of analyzed samples. Continued development of in-situ techniques could rapidly identify the diversity of materials within and between terrains.

If fast and accurate enough, these techniques could help ensure that collected samples — whether for return to Earth or further in-situ analyses — include all scientifically important components. For example, astronauts or rovers could target the collection of low-abundance materials in a site otherwise dominated by another sample type. This could reduce the need for "luck" or for collecting vastly more sample mass than needed.

A limited amount of sample preparation (e.g., grinding to smaller fragments or powder, heating, chemical digestion) may be required for some in-situ analyses, as the Mars rovers have demonstrated. However, many lunar samples (e.g., Figure 1) exhibit such complex, small-scale heterogeneity that comprehensive, in-situ sample preparation will likely be impractical in many situations. Some lunar science goals will require delivery of a prepared, high-quality sample to a suitably accurate and precise instrument.

Returned samples –
For Apollo samples, tens of thousands of component pieces have been painstakingly extracted and prepared for laboratory analyses. This work has been conducted across five decades by the sample processing team at curation facilities at NASA's Johnson Space Center in Houston and hundreds of scientists in other labs around the world.

The analysis and cataloging of these samples involves many hours of work in various combinations of separation, extraction, chemical processing, and other means of preparation for each individual sample. Different combinations of sample preparation are implemented for different types of scientific analysis. For many types of analysis, a final step in sample preparation is dissolving a sample in acid (e.g., nitric acid, hydrochloric acid, hydrofluoric acid), which allows individual elements to be filtered and separated for analysis by increasingly sophisticated and capable mass spectrometers. For all these complexities and more, the return of samples to Earth will remain central to lunar science for the foreseeable future.

Sample Characterization

There have been over 3,380 separate studies of the Apollo samples over the past 50+ years. They have yielded many thousands of scientific papers, which is a testament to the complexity and the long-term value of returned samples.

Sample characterization — that is, gaining a better understanding of the basic nature of individual puzzle pieces and how the puzzle pieces fit together — is an essential step in studying returned lunar samples. The same is true for returned asteroid samples and lunar and Martian meteorites and is expected for the Mars Sample Return mission.

Optical microscopy provides magnified views of the sample surface. X-ray computed tomography enables views of the interior of samples to record the position of pieces and informs decisions about where to slice open a sample (just as dentists and doctors use X-rays to inform treatment plans). Following mechanical preparation, researchers use additional optical and electron microscopy technologies and various spectroscopies over a wide range of the electromagnetic spectrum to provide much higher resolution views of the sample interiors.

Once basic sample characterization is complete, more detailed types of analyses can be conducted to evaluate the history of the sample and its components. For example, scanning electron microscopes and electron microprobes enable chemical and mineralogical analyses at nanometer to micrometer scales. At these scales, important records of lunar processes are recorded by variations in chemistry and mineralogy. Similarly, focused ion beam instruments enable extraction of electron-transparent wafers for analysis by transmission electron microscopy. This method provides exceptionally detailed views of chemical and mineralogical variations at sub-nanometer resolution.

These are workhorse techniques — required analytical capabilities — for understanding lunar samples. The data produced by these techniques are imperative for achieving many Moon to Mars Objectives.

In-situ analyses –
The development of miniaturized scanning electron microscopes (e.g., Mochii, which flew on the International Space Station) demonstrates a viable future path for some detailed sample characterization in situ, albeit with some limitations regarding surface sample preparation. Other techniques, such as laser Raman spectroscopy, have been deployed on Mars rovers and provide similar opportunities for characterizing sample chemistry.

However, techniques like X-ray computed tomography have yet to be employed in a mission setting but could provide useful information on the 3D interior structure and mineralogy of lunar samples in the future. Example use cases would include uncrewed missions or extended-duration stays; sample triaging would require significant improvements in speed and automation to be useful on shorter missions.

Returned samples –
Many sample characterization techniques require long-duration analyses (hours to days) to study even a few millimeters of material. Other techniques for sample characterization are currently far beyond the capabilities of in-situ instruments.

For example, characterizing very small but significant features (e.g., delicate surface structures, diagnostic chemical zonation at mineral boundaries) requires techniques such as transmission electron microscopy and associated focused ion beam preparation. The size, complexity, and underlying technologies of this method would be extremely challenging to miniaturize for flight.

The use of synchrotron facilities, requiring kilometer-scale light paths, enables exceptional chemical and mineralogical investigations at high spatial resolution, with applications to lunar science goals ranging from understanding magmatism to exploring the effects of space weathering. It is currently unfathomable to miniaturize the enormous infrastructure supporting such facilities for in-situ analyses.

Accuracy and Precision

Essentially every element in the periodic table has value in lunar science. For example, volatile elements, such as hydrogen, and dozens of related molecules (e.g., H, OH, H2O, CH4, NH3) are integral to Artemis science and exploration objectives in the lunar South Pole region.

Hydrogen is also one of almost 60 elements that have more than one stable isotope (elements with the same atomic number but additional neutrons resulting in different atomic mass). For these elements, fractionation of light and heavy isotopes preserves the effects of important physical and chemical processes (e.g., melting, evaporation, crystallization, metal-silicate fractionation during core formation).

Many elements also have unstable isotopes, some of which yield useful systems for radiometric dating (e.g., U-Pb, Sm-Nd, Rb-Sr, K-Ar). This dating provides ages that, at the right levels of precision, can answer questions of when key events happened in a moon or planet's history, ranging across primary formation, impact modification, and surface exposure.

In-situ analyses –
While many science goals require accuracy and precision beyond the capabilities of current flight hardware, some science goals are ideal for in-situ analyses. One such example is the Dating an Irregular Mare Patch with a Lunar Explorer (DIMPLE) instrument suite, which was selected in 2023 for funding by NASA's Payloads and Research Investigations on the Surface of the Moon (PRISM) program.

DIMPLE will be delivered to the Moon by a Commercial Lunar Payload Services (CLPS) lander. Its instrument suite includes the Chemistry Organic and Dating Experiment (CODEX), which will yield the first in-situ dating of samples on the lunar surface.

CODEX has an estimated precision of ± 375 million years, leveraging the rubidium-strontium (Rb-Sr) radiometric system. While this precision would not be suitable for most lunar chronology analyses, it is sufficient to achieve the specific goal of the mission: determining whether the unique terrain of Ina, an unusual depression on the lunar surface, is ancient (approximately 3.75 billion years) or young (approximately 10–100 million years).

Other in-situ analyses, such as the detection of volatiles (e.g., water), are central to other CLPS missions, NASA's Volatiles Investigating Polar Exploration Rover (VIPER), and multiple concept missions and instruments. Volatiles are central to many science goals and to the broader Moon to Mars Objectives. Low-mass, uncrewed missions can explore far more sites and the results can inform strategic site selection for larger and crewed missions in the future.

Returned samples –
Laboratories on Earth have significantly higher accuracy and precision than is possible with in-situ instruments. In most instances, this accuracy and precision is required to answer driving science questions.

For example, the vast majority of questions regarding the ages of terrains, regions, and volcanic or impact events on the Moon (LPS-1,2,3; e.g., the age of the South Pole-Aitken basin) require significantly better precision than current flight instruments offer. For comparison, laboratories on Earth in the Apollo era had comparable precision to CODEX, while modern terrestrial laboratories are capable of Rb-Sr dating with precision of approximately 30 million years, 10 times better than the CODEX instrument.

Further, Rb-Sr is just one dating technique; it is appropriate for understanding only a subset of events and processes that have occurred throughout lunar history. The return of samples enables researchers to apply multiple dating techniques (e.g., K-Ar, Sm-Nd, U-Pb) to multiple mineral phases even within a single rock sample; this is important because some isotopic systems are more prone to resetting during impact events than others.

Similar scenarios exist for other elemental and molecular analyses. For example, understanding the origin and evolution of volatiles, both for science and in-situ resource utilization, may require analyses of low-abundance elements and at levels of isotopic precision that are difficult to achieve through in-situ analyses. Return of samples to Earth enables many different types of specialized instruments to study each element, isotope, and molecule. Essentially every instrument on Earth becomes part of the analytical suite.

Development of different instruments enables researchers to tailor analytical conditions to maximize the accuracy and precision of a specific analysis. Many of these instruments rely on exceptionally heavy magnets to provide sufficient mass separation between different isotopes. Even a small suite of mass spectrometers capable of measuring a handful of groups (e.g., light elements, transition metals, heavy radiogenic isotopes, noble gases) requires many metric tons.

Researchers need these instruments and dedicated components because of the very slight differences in chemistry that are imparted by geological processes — often variations measured in parts per million or parts per billion.

Suites of Instruments

It is common practice — and essential for achieving many scientific goals — to analyze the same sample with multiple techniques. This enables researchers to place the different puzzle pieces in the right context, (e.g., which are older or younger, which formed at higher temperatures, which formed close together, which were brought together by a later impact event).

In-situ analyses –

The development of an architecture that supports larger payloads opens the possibility of landing instrument suites for in-situ analyses. Such an approach can enable detailed sample science in the absence of sample return.

The Mars rovers exquisitely demonstrate the level of science that can be achieved by integrating results from multiple types of instruments. CLPS, autonomous rovers, and crew deployment will provide multiple opportunities for the development and implementation of such instrument suites for the Moon. The deployment of carefully selected instrument suites could offer excellent site context, answer a subset of science questions, inform future mission decisions, and support contemporaneous or future sample return activities.

Returned samples –

Just as with the Mars rovers, even long-duration exploration with a comprehensive instrument suite will leave many significant science questions unanswered. The expense and complexity of the Mars Sample Return mission is well known, yet the call for the mission continues for a simple reason: in-situ instruments cannot match the fidelity of science enabled by returned samples.

The same is true for the Moon and, thankfully, the return of samples from the lunar surface is highly feasible. Returned samples allow researchers to employ many different approaches on the same sample and multiple sub-samples using dozens of instruments across the best laboratories on Earth.

Such approaches enable deep understanding of how, where, and when a sample was formed — and what this tells us about the origin and evolution of the Moon, as well as other bodies within the solar system. A huge advantage of returned samples is that they also enable new analyses to be conducted as technology develops over many decades.

Beyond Geology-Based Science

The bulk of this paper is dedicated to sample science from a broad geological perspective, but similar needs for sample return exist in other disciplines.

For biological and physical sciences conducted on the lunar surface or in cislunar orbit, the return of specimens for detailed analyses in Earth-based laboratories is critical. Biological investigations require different types of analyses at various levels of physiology. These identify underlying root mechanisms both affected by and governing responses to the space exploration environment by understanding impacts to individual and integrated multi-organ systems.

Microbiology ecosystem and pathogenicity investigations require analysis of individual specimens at the genetic level through host-microbial interactions and microbe-to-microbe interactions. In-situ analyses will provide important rudimentary data that requires more expansive follow-up analyses using instruments and techniques that, for now, are only available in Earth-based laboratories.

In addition, the return of specimens will require either live return or conditioned stowage (freezers), which enables high-fidelity preservation of the specimens for morphology, biochemical, and molecular biological analyses. Cold stowage may also be required for the transport of accessory chemicals and solutions for in-situ analysis instruments and of the specimens themselves.

Although much of the data and imagery for physical sciences investigations can use telemetry back to Earth, some investigations will require sample return to complete the analyses. For example, elements and materials used for combustion and flammability studies will require post-burn analyses to understand and develop models for propulsion and fire safety. Products created from science instruments examining the fundamental properties of materials, braising, volatile extraction, and soft matter/granular flow and particles are important to close knowledge gaps for development of lunar in-situ resource utilization methods and processes. These must be analyzed in Earth-based laboratories with instruments capable of the depth of analyses required. In addition, if telemetry bandwidth is limited, the return of data recorders and memory cards will be required.

Collectively, the return of specimens and samples from the Moon is important to gain a complete understanding of biological and physical systems. This understanding is critical to advancement of scientific knowledge, closure of knowledge gaps, and development of biological and predictive models that can be used to advance safe and productive human exploration, deep space travel, and long-term self-sustaining habitation on the Moon and other worlds.

Conclusion

Sample return is an absolute necessity to properly achieve the lunar/planetary science goals of the Moon to Mars Objectives. Returned samples enable analyses by the world's best laboratories and instruments, supported by teams of scientists and engineers. Returned samples will also serve as ongoing resources to the worldwide scientific community for the coming decades, enabling fundamental insights into the Moon and other bodies in our solar system.

In-situ analyses/instruments can address a subset of the lunar/planetary science goals, and deployment of in-situ instruments to multiple lunar terrains during low-mass, uncrewed missions will provide broader insights than can be achieved through larger and/or crewed missions alone.

Many of the inherent limitations of in-situ analyses (e.g., sample preparation, accuracy and precision, time needed for analyses) mean that even a fleet of in-situ instruments would not currently address many lunar science goals. However, continued development of in-situ instruments will ensure that they are capable of more and more unique, standalone science in the future. Further, as we test and develop in-situ technologies on the Moon during the early Artemis missions, NASA can leverage these expanding capabilities for long-duration crewed missions to the Moon and future missions to Mars.

Overall, the most efficient strategy for lunar science and exploration includes careful integration of in-situ analyses and sample return. Current and anticipated near-term in-situ analytical capabilities do not replace the need for sample return; the balance between the two should be carefully considered on a case-by-case basis, with science representatives involved in all stages of mission concept and architecture definition.

Mars Mission Abort Considerations

Overview

Throughout the history of human spaceflight, astronauts have never been more than a few days (and rarely more than a few hours) from Earth. Aborts for missions to low-Earth orbit or the International Space Station are relatively short. Aborts for lunar missions may be longer than aborts from Earth vicinity but are still measured in days.

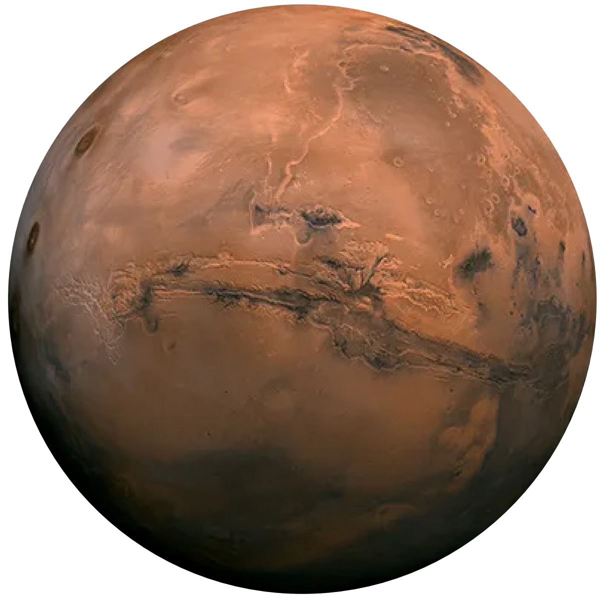
On the transit to Mars, mission abort is a much more complicated event because of the sheer distance between Earth and Mars. The distance and scale differences between missions to the Moon and Mars mean lessons learned from lunar mission aborts will have limited direct applicability for Mars. Depending on when an abort is initiated in a Mars mission timeline, the heliocentric nature of transit — in orbit around the Sun — may require many months to return to Earth, regardless of the transportation system selected.

For transportation architectures that refuel in Mars vicinity, mission abort during outbound transit may not even be possible. In many cases, transit abort may not be a practical response to an emergency because the time to return the crew may exceed the crew's ability to stave off the emergency.

Early human Mars missions will also have limited abort options for descent to and ascent from the surface.

- **For descent —** where abort means returning to orbit — Mars' atmosphere and gravity will make it difficult to carry sufficient on-board propellant to initiate an abort for a human-scale payload.
- **For ascent —** where abort means returning to the surface — Mars will initially lack the specialized surface infrastructure and staffing needed to aid crew after the abort. Even a successful abort to the surface may leave crew stranded, far away from assets necessary for a safe return to Mars orbit.

Both of these challenges will require an entirely new contingency operations paradigm relative to our flight experience nearer to Earth.



Transit Abort Analysis

Due to the nature of celestial mechanics, abort maneuvers are inherently more challenging than nominal mission maneuvers. To understand the fundamental nature of these abort maneuvers, NASA evaluated three propulsion concepts for a crewed Mars mission. This initial scoping assessment assumes an example trajectory with a roundtrip duration of 850 days with a short stay in Mars vicinity.

The three transportation propulsion concept scenarios analyzed were:

- A hybrid abort, where a low-thrust hybrid nuclear electric propulsion (NEP) and chemical propulsion system utilizes both stages to perform abort maneuvers.
- A NEP-only abort, where the hybrid NEP and chemical propulsion system jettisons the chemical propulsion stage and utilizes only the low-thrust electric propulsion system.
- A ballistic abort, where a high-thrust propulsion system (e.g., a nuclear thermal propulsion [NTP] or all-chemical propulsion system) performs the abort maneuvers.

In all three cases, the analyses assumed that the transportation systems depart Earth with only enough propellant for the expected round-trip mission. Scenarios in which the propulsion system carries abort-specific contingency propellant were outside the scope of this initial assessment.

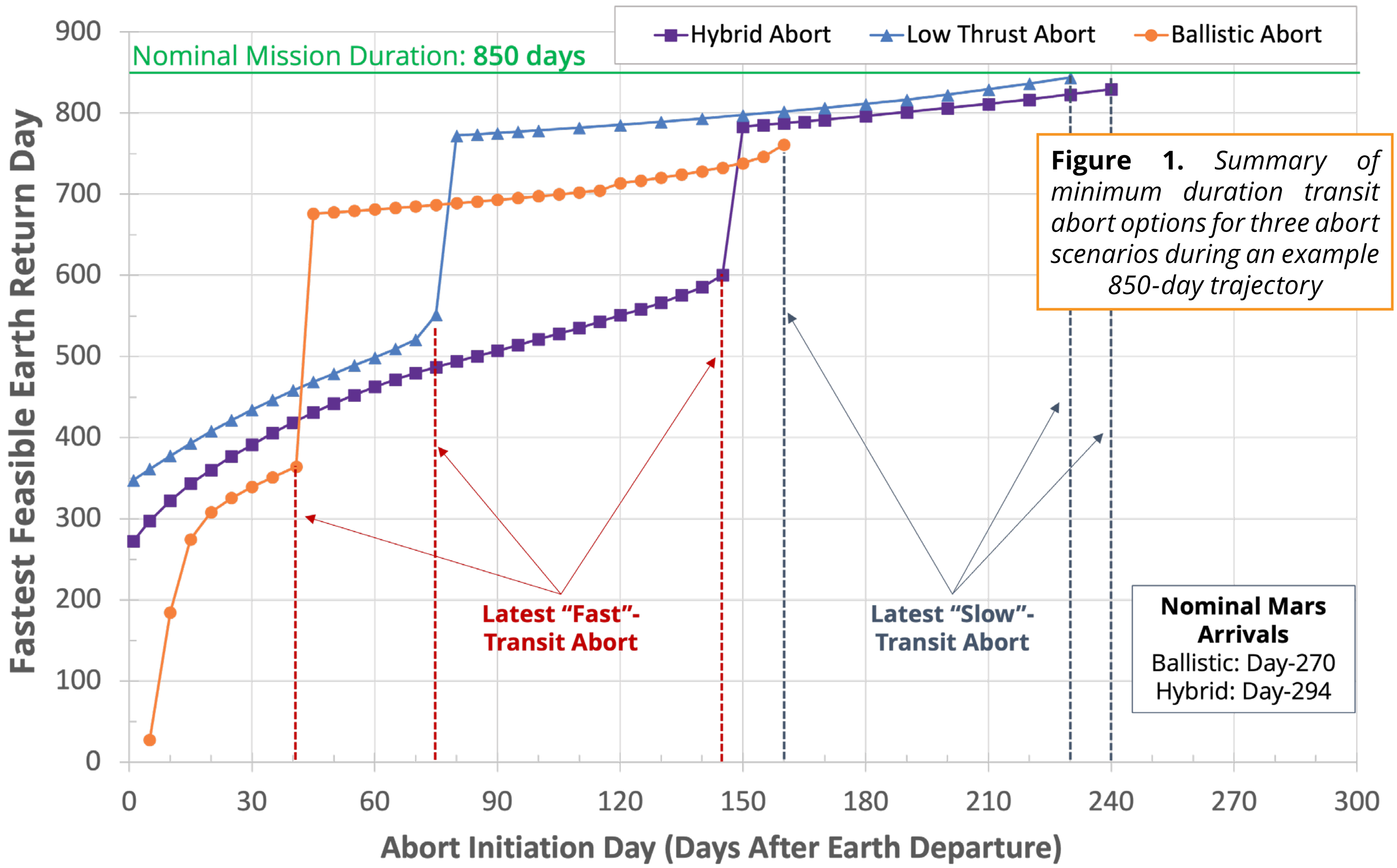
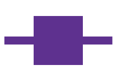


Figure 1. *Summary of minimum duration transit abort options for three abort scenarios during an example 850-day trajectory*

Figure 1 summarizes the minimum duration abort utilizing all remaining propellant as a function of the day abort is initiated for the three scenarios.

High-thrust, ballistic aborts using NTP or all-chemical systems provide an advantage if abort is initiated within a few days of departing Earth.



An abort using hybrid low-thrust systems can enable faster Earth return if initiated after 45 days.

A low-thrust hybrid system operating only on electric propulsion could still enable a faster return to Earth than high-thrust systems if abort is initiated between mission days 45 and 75, even with the loss of its chemical stage.

However, these differences may be inconsequential. An abort initiated beyond about 30 days of Earth departure will require a year or more to return to Earth in all cases. If a mission initiates an abort due to a life-threatening emergency like a failure of critical life support systems, a loss of crew is likely regardless of whether their transportation system is capable of returning to Earth by day 310 versus day 390.

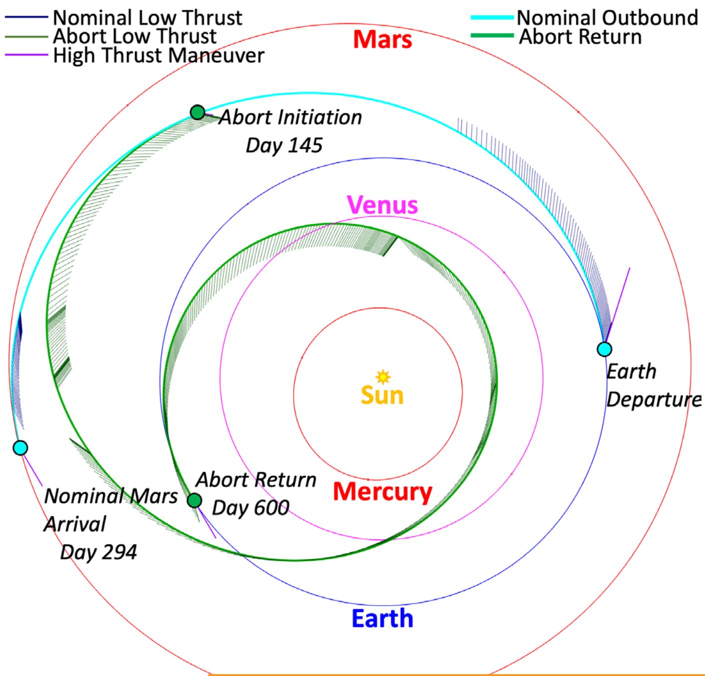
To better understand these performance curves, it is necessary to understand the two classes of abort trajectories available:

- In a fast-transit abort, the spacecraft flies closer to the Sun to increase its relative velocity to Earth for a faster rendezvous.
- In a slow-transit abort, the spacecraft increases its distance from the Sun to reduce its relative velocity to Earth, allowing Earth to catch up for the rendezvous.

In this case, "fast" and "slow" are relative; even just a few weeks after departing Earth, the time required to return to Earth increases dramatically. An abort initiated on day 30 of a Mars mission would result in a return to Earth nearly a year later — on mission day 300+ — regardless of propulsion system. This fundamental shift in abort definition from previous crewed exploration campaigns is one of the primary findings of this analysis.

A ballistic abort utilizing high-thrust maneuvers and fast transit can return to Earth earlier than a hybrid propulsion abort. However, the availability of fast-transit abort is limited to about the first 40 days of the mission. After mission day 40, a ballistic abort is limited to slow-transit, while a hybrid propulsion system may pursue a fast-transit abort through day 75 if NEP-only and through day 140 if NEP and chemical.

These estimates only consider this specific mission trajectory and these transportation system conceptual



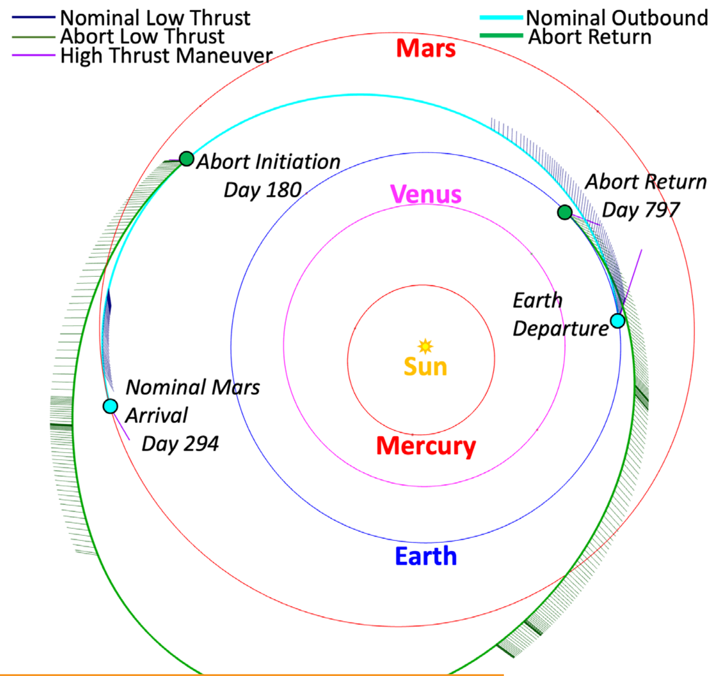


Figure 2. *Example "fast" transit (left) vs. "slow" transit (right) abort trajectories for an example 850-day short Mars vicinity stay–class roundtrip mission to Mars*

designs. They may vary with other mission trajectories or concepts. The analysis shown here is not meant to generalize all abort scenarios. Abort capabilities are specific to a given scenario, with both abort availability window and return to Earth duration dependent on the exact situation that necessitated the abort.

Fast-transit aborts would present significant challenges in thermal and radiation management, as the trajectory would push a mission significantly closer to the Sun than the expected mission trajectory. Spacecraft systems would need design modifications for these contingency scenarios to ensure crew safety.

Hybrid propulsion systems have wider abort windows for slow-transit aborts compared to the ballistic option. However, these aborts are significantly longer in duration and may mitigate less risk to a crew.

Risk mitigation for abort scenarios is a complex problem with many competing metrics. Without a holistic view of the integrated problem, it would be misleading to use abort as a discriminating factor between different transportation system options.

Additional details of this analysis may be found in the NASA-authored technical publication referenced below.

Key Take-Aways

A Mars transit abort will not mean an immediate return to Earth, regardless of the chosen propulsion system. Mission aborts will be measured in months, not days.

At Mars, there will be limited ascent or descent abort options for early human exploration missions.

Abort planning for crewed Mars missions requires a fundamental shift in thinking regarding reliability, crew risk, contingency planning, and mission operations.

To meet NASA's Moon to Mars Objectives, mission planners must develop a new operational paradigm. Mission abort alone will not be useful for crew risk mitigation.

Abort considerations will have flow-down impacts on vehicle design, redundancy and sparing strategies, and contingency planning. Understanding the complex interplay of these factors is the first step in developing a safe, reliable transportation system for crewed missions to Mars.

Reference

Chai, P. and M. Qu, H*uman Mars Mission Transit Abort Options for Ballistic High Thrust and Hybrid Transportation Systems*, AIAA 2022-4374, AIAA ASCEND, October 15, 2022. https://doi.org/10.2514/6.2022-4374

Mars Communications Disruption and Delay

Overview

The communications disruption and delay profile for a Mars mission will depend on the trajectory profile of the mission, though some generalizations can be made. While several factors can contribute to communications disruption and delay, this paper addresses the unique physical characteristics of Mars transit and Mars-vicinity operations.

Assuming nominal operation of communications systems, disruption occurs when the Sun or other planetary objects are directly between Earth and a spacecraft, rover, or other element. This obstruction severs the line of sight as the signal travels between Earth and Mars and results in a communications blackout. Interference from solar radiation can also degrade that signal without full obstruction.

The duration of a blackout depends on the communications protocol and signal strength. For any crewed, roundtrip mission to Mars, direct spacecraft-to-Earth communications blackouts are inevitable and can last weeks. Depending on the mission profile, these blackout periods can occur while the crew is in transit or the vicinity of Mars. NASA analyses show that blackout periods generally occur while the crew is at Mars for long-stay missions, and during transit for higher energy, short-stay missions.

For communications delays, the time required for signal to travel from Earth to a Mars element and back is a function of the distance separating the two. Communications signals travel at the speed of light in a vacuum, so signal transit time is the element's distance from Earth divided by the speed of light.

The exact profile of the delay will depend on trajectory, but the one-way communications delay for a crewed Mars mission can be upward of 21–23 minutes, with the longest delays occurring while the crew is at Mars or just after Mars departure.

Communications disruptions and delays for crewed Mars missions necessitate significant crew and system autonomy from Earth-based mission control, which drives certain system and operational requirements. Communications relay assets could potentially provide some relief from communications blackouts but would not eliminate delays, as the signal must still travel the same distance or farther to reach its destination.

Background

Approximately every 26 months, Earth and Mars are on exact opposite sides of the Sun. Astronomers call this celestial phenomenon — where all three celestial bodies are in a straight line — "conjunction." Figure 1 illustrates this feature that results from the relative orbits of planets.

Conjunction presents a challenge to any Mars mission in that it results in a communications disruption. This is because communications signals cannot pass through the Sun directly. The Sun also distorts any signals that pass too close due to the interference of solar energy.

For robotic missions, operations during these conjunctions are typically managed to reduce impacts on science objectives and increase spacecraft safety. Operating robotic platforms in safe mode and standing down of any operational activities reduces risk during a conjunction. However, those options are not available to a crewed mission, as crew activities must continue even in the absence of direct communications with mission control.

The extent of any communications disruption or blackout depends on communications equipment and sensitivity to interference from solar energy. A graphical representation of that angle, θ, can be seen in Figure 1. Communications equipment highly sensitive to solar interference would experience communications disruption with a higher value of θ.

Figure 1. *This diagram illustrates Earth-Sun-Mars conjunctions creating line-of-sight disruption between Earth and Mars (left) and the angle definition for communications disruption analysis (right).*

For the initial assessment of the blackout period during Mars missions, NASA assumed a θ value of 2° based on the current understanding of communications protocols and their susceptibility to signal disruptions. However, higher bandwidth communications protocols may have higher sensitivity to disruptions and could have a higher θ value.

Example 850-Day Short-Stay Roundtrip Mission to Mars

Figure 2 shows the communications disruption and delays for a representative, 850-day, short-stay mission to Mars. The top chart shows the Sun-Earth-spacecraft angle, and the bottom chart shows the one-way communications delay profile for this representative trajectory.

A 2° θ angle results in a communications disruption of three weeks of blackout around 450 days into the mission, about 100 days after the crew departs Mars from their surface mission. This three-week period of communications disruption and blackout would require significant crew and system autonomy from mission control. This drives certain system capabilities, redundancies, and operational needs for mission design and/or the addition of communications relays.

Example 1000-Day Long Mars Stay–Class Roundtrip Mission

Figure 3 shows the communications disruption and delays for a representative, 1,000-day mission typically associated with a minimum-energy roundtrip mission to Mars. Assuming an Earth-Sun-spacecraft angle threshold of 2°, the trajectory results in a communications blackout period of approximately 13 days during the phase of the mission in the vicinity of Mars.

Depending on the surface concept of operations, the crew could be on the surface of Mars performing exploration duties. This blackout period occurs about 100 days into the 300-day stay in the vicinity of Mars. This means critical events related to planetary arrival and departure should not be impacted by the disruption. For delays in communications, the blackout period coincides with the longest delay period of just over 20 minutes one-way, 100 days after Mars arrival.

Summary

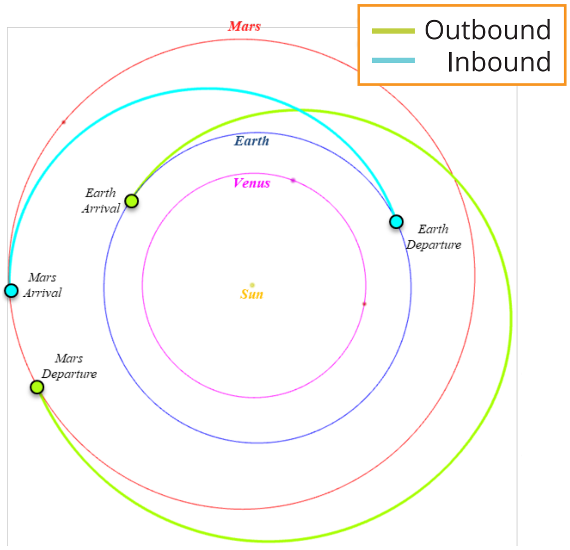
Communications blackouts and delays are unavoidable for crewed missions to Mars, though blackouts could be mitigated with communications relay elements. The design of crewed Mars missions must reflect this shift in communications paradigm when compared to low-Earth-orbit or lunar missions.

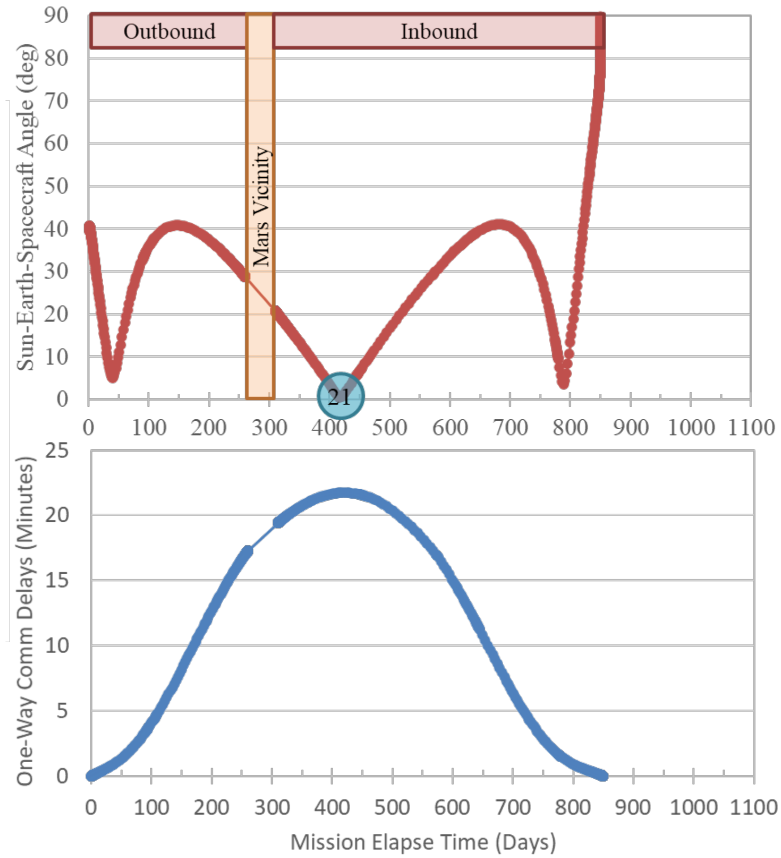
System and crew autonomy should be a significant focus in Mars mission design. NASA analyses can provide representative mission profiles, with estimated communications delays and blackout periods to inform those design parameters.

References

McBrayer, K., Chai, P., Judd, E., Communication Delays, Disruptions, and Blackouts for Crewed Mars Missions, AIAA ASCEND, 2022

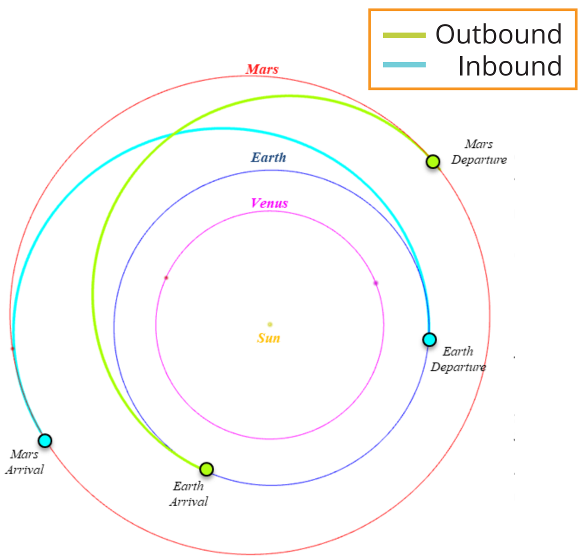
Figure 2. *Communications disruption and delay for an 850-day, short-stay, roundtrip Mission to Mars with a communications blackout of about 21 days and maximum one-way communications delay of 22 minutes. Both blackouts occur during the inbound leg of interplanetary transit.*

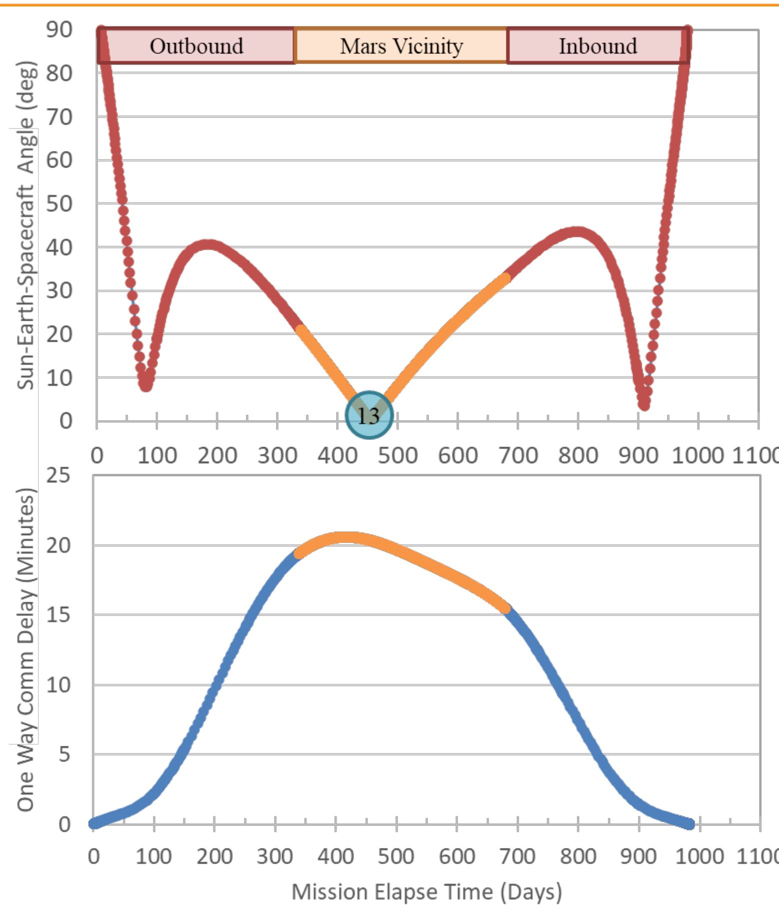




Deep Space Duration: **850 days**
Mars Vicinity Duration: **51 days**
Solar Distance: **~1.0AU to ~1.8AU**

Figure 3. *Communications disruption and delay profile of a representative minimum energy, approximately 1,000-day stay, roundtrip mission to Mars with a communications blackout of about 13 days and a maximum one-way communications delay of 21 minutes. Both occur while the crew is in Mars orbit or on the surface of Mars.*





Deep Space Duration: **985 days**
Mars Vicinity Duration: **~300 days**
Solar Distance: **~1.0AU to ~1.6AU**

Mars Surface Power Generation Challenges and Considerations

Background

Once the challenges of reaching and landing safely on Mars have been met, the first human explorers will be faced with the challenge of finding sufficient energy to power the systems they will need for a healthy and productive stay on the surface and for their ascent back to orbit. Surface power needs may vary from one human Mars mission to another depending on how long each crew plans to stay on Mars, their surface mission objectives, and the support services their surface and ascent vehicles will require.

Studies show that a very modest mission of two crew members, conducting science and exploring the surface for no more than 30 days while living in a pressurized rover — plus propellant conditioning for a small, storable-propellant crew ascent vehicle — will require at least 10 kilowatts (kW) of surface power. At the other end of the trade space, a larger crew complement, exploring the surface for a longer duration, use of cryogenic ascent propellant manufacturing and storage, etc., will require hundreds of kW, approaching megawatt (MW)-class power systems for some architectures.

Surface power system designs for early human Mars missions must account for not only crew life support, but ascent vehicle preparation, propellent quantities, and equipment keep-alive power. This white paper outlines some of the unique challenges that Mars poses to ensuring sufficient power is generated, particularly during the initial human Mars segment.

Unique Mars Environmental Surface Power Challenges

Dust Storms

Martian dust storms have been observed in sizes ranging from small, local dust devils to regional and even global storms. Regional storms can cover thousands of square kilometers and last for days to weeks, growing in size and moving from their points of origin based on atmospheric conditions and terrain features. Global dust storms encircle the entire globe, can persist for several weeks or months, and may evolve from a local phenomenon to a global event in just a few Martian days (called sols).

Because the atmosphere is so thin and dry, it takes much longer for fine dust particles to settle out of the atmosphere, which places solar array–powered systems at particular risk. Data collected by the Opportunity rover during its fatal encounter with a global Mars dust storm in 2018 demonstrates just how fast and furious Martian weather can be: from clear skies to as dark as Opportunity had ever previously recorded (4.9τ), within three Martian sols.

Opportunity then observed a virtual blackout (Figure 1A) just four sols later, with its final message reporting more than double prior recorded optical measurements. The 2018 storm shrouded the entire planet in such a thick blanket of dust (Figure 1B) that even the Curiosity rover, operating on the other side of the planet, reported significant optical degradation. However, unlike the solar-powered Opportunity, Curiosity's nuclear radioisotope power system was unaffected by the storm, allowing it to continue transmitting data to Earth.

The impact of Martian dust storms on surface power will depend on severity and duration. Regional and global storms pose significant risk to surface power systems in two ways: first, dust suspended in the atmosphere will reduce the amount of energy reaching surface power systems that rely on solar energy, such as solar arrays, and can disrupt power systems that require clear line of sight for distribution, such as power beaming technologies. Oversized arrays can compensate for some reduced array efficiency, but at very high solar obscuration even oversized arrays may not be able to collect enough solar energy for nominal surface operations and energy storage systems to wait out the dust storm event could be enormous.

The second problem is that dust settling out of the atmosphere can accumulate on solar

Figure 1a. *Simulated view of the Sun from Mars during a dust storm*

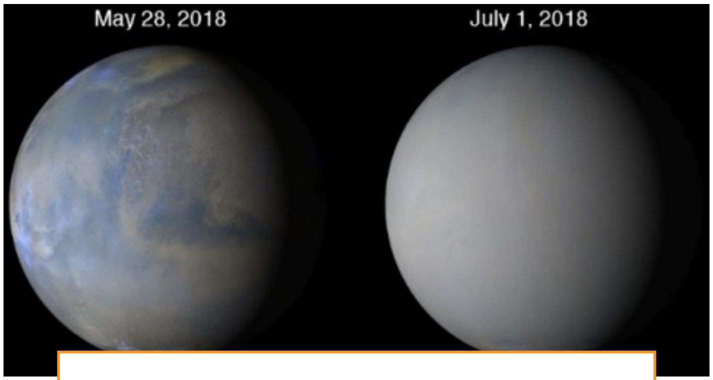


Figure 1b. *Global view of Mars during the 2018 dust storm*

arrays, further reducing their efficiency. For example, NASA's InSight Mars lander was able to achieve all of its primary science objectives, but heavy dust accumulation prevented the solar arrays from generating sufficient keep-alive power and forced controllers to suspend operations after the vehicle was no longer able to communicate with Earth.

Reduced Solar Energy Availability

Solar energy has long been the reliable choice for in-space power applications, but solar array designs on Mars must account for reduced solar flux, which is at most 45 percent of typical Earth solar flux values and varies significantly with geographic location and season. Figure 2 presents the maximum solar flux in orbit and at several different latitudes over a typical Martian year. The dashed curves in Figure 2 show the potential impact of dust storms on solar flux.

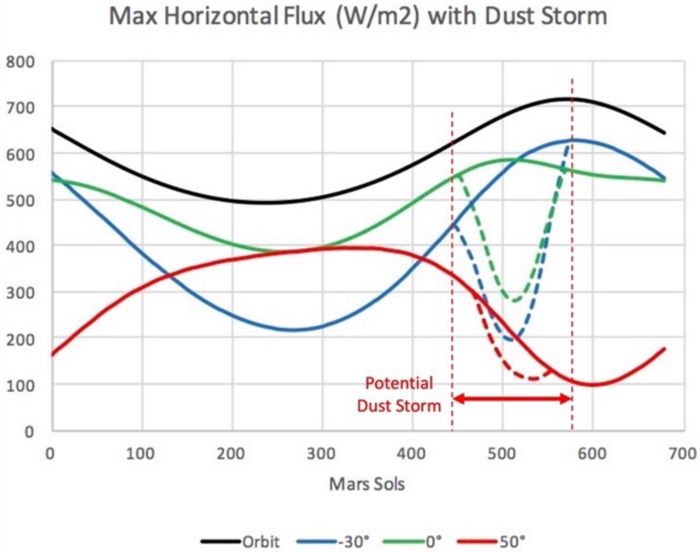


Figure 2. *Mars Solar Flux Variations*

The Martian day/night cycle also varies with location and season. Typical mid-latitude missions would experience a 25-hour cycle, with approximately 50 percent of the time spent under illumination. In practice, this means that a solar power system must be oversized to supply power for daylight operations while simultaneously charging the energy storage (batteries or regenerative fuel cells) to maintain night operations, all of which requires additional landed mass/volume and complexity.

Gravity and Wind Loads

Although Mars gravity is only about a third of that on Earth, Mars has about twice the gravity of the Moon, meaning that large array structures designed for lunar applications would need higher structural strength for deployment on Mars.

Unlike the Moon, Martian winds pose another unique challenge. The Martian atmosphere is very thin, and even very high wind speeds would impose lower forces than equivalent wind speeds on Earth. For example, the highest wind speed ever measured on the Martian surface was about 30 meters per second (m/s) at the Viking 2 Lander site, but the lower atmospheric density on Mars makes a solar array in that same wind feel like it is only in a 4 m/s terrestrial wind.

However, even though the pressures felt by a solar array are lower on Mars, they are still exerting forces in addition to gravity that can be quite substantial. The design of very large or vertical solar arrays must account for these forces.

Severe dust storms beg an obvious question: why not just harness the power of Martian wind? While winds must be accounted for structurally, the Martian atmosphere is too thin to generate sufficient wind power for crewed systems. Data collected by InSight reveals that winds at Elysium Planitia rarely reached a capable power threshold; the wind was even insufficient to reliably blow dust off of arrays. In short, Martian winds may be troublesome, but are insufficient to be harnessed.

Day/Night Cyle Temperature Variations

The Martian day/night cycle is comparable to Earth's; a Martian sol is about 39 minutes longer than an Earth day. This means that solar-based power systems must be augmented with overnight energy storage solutions. Mars surface temperatures also vary from as warm as 30 C to as cold as -140 C, depending on location and season.

Unique Mars Operational Challenges

Autonomous/Remote Power System Operation

Round-trip human Mars surface systems are dominated by the ascent vehicle needed to launch crew back to Mars orbit and return to Earth. In most mission architectures, the ascent vehicle is the largest and heaviest surface payload, making it difficult to land a fully fueled ascent vehicle.

To mitigate landing risks, many architectures rely on landing the ascent vehicle with empty or partially full propellant tanks and either transferring Earth-origin propellant that was delivered on a separate lander or manufacturing propellant from Mars resources. All approaches require abundant surface power.

At a minimum, a few kW will be needed to environmentally condition Earth-origin propellants until ascent vehicle use. In contrast, tens of kW will be needed to maintain cryogenic propellants. Additional power will be needed to transport propellants between landers. Manufacturing propellants from Mars resources will require tens to hundreds of additional kW.

To reduce crew risk, the ascent vehicle will ideally be ready prior to crew arrival, so whether ascent propellants are delivered from Earth or manufactured in situ, Mars surface power systems must be deployed, checked out, activated, and maintained without human intervention or assistance. Depending on pre-deploy mission timing (which will be constrained both by vehicle availability and the 26-month Earth departure windows of opportunity for Mars), and surface concepts of operations, surface power systems may need to be deployed years in advance of crew arrival and may need to support several crew missions over a years-long, multi-mission campaign.

Limited Repair Options

The sheer distance between Earth and Mars means that unplanned replacement units or repair parts will not be available. Critical crew safety capabilities, such as surface power, will drive reliability, redundancy, and possible spares provisioning mass, all of which will have flow-down impacts to other parts of the architecture and operations.

Because loss of surface power can lead to loss of mission/loss of crew risk on Mars, power system spares must also be considered in mass and volume calculations when comparing different power source options. This includes a variety of failure modes during the crewed landing phase concept of operations: dust storms could delay the crew's connection to existing surface power sources, or the crew could land farther away from the pre-deployed power source than planned.

Plume/Surface Interactions

A particular challenge for Mars surface assets, including power systems, is potential impact of descent and ascent engines' thrust plume debris, which is exacerbated by the Mars atmosphere. Power system separation from arriving/departing vehicles may require longer power distribution systems (e.g., power cabling) or power system handling and surface mobility. Because power systems must be deployed in advance of crew arrival, power system handling, mobility, and power distribution must also be performed autonomously or remotely without crew assistance. If sufficient separation distance (currently estimated at about 1 kilometer) is possible, surface power systems may require additional debris protection to mitigate potential debris impact damage.

Planetary Protection Constraints

Planetary protection refers to "the policy and practice of protecting current and future scientific investigations by limiting biological and relevant molecular contamination of other solar system bodies through exploration activities and protecting the Earth's biosphere by avoiding harmful biological contamination carried on returning spacecraft, as described in the Outer Space Treaty."[1]

Specific policy guidelines are being developed to establish quantitative and implementable planetary protection requirements for the safe and sustainable exploration and utilization of Mars. Eventual requirements may include sterilization goals to prevent the transmission of Earth-origin microorganisms to Mars, or operational constraints, such as limits on thermal output that could inadvertently create a more habitable environment for microorganisms.

Mars Surface Power Generation Opportunities

Surface Power Generation Technologies

Despite Mars' many challenges, promising power generation technologies are available or in development. High energy density nuclear power, either Curiosity rover-style radioisotope power system or fission systems, are unaffected by day/night cycles or weather and package well in volume-constrained spacecraft. Although current radioisotope power system designs only offer a few hundred watts, they may be applicable to smaller power load applications. For higher power crew life support or ascent propellant manufacturing needs, fission surface power is readily scalable.

Limited solar power may be feasible if augmented by robotic dust wipers, pressurized gases, mechanical array tilting, or electrodynamic or piezoelectric dust removal to clear accumulated dust from the solar arrays, although only for applications that are not crew safety critical, given that surface dust removal would not mitigate the problem of suspended atmospheric dust during lengthy storms. Unique operational considerations, such as radiation keep-out or large array off-loading, would need to be evaluated for Mars.

Lower technology readiness solutions may eventually offer additional options. For example, geothermal energy has been proposed for use in eventual Martian settlements, but data on its availability is limited. Accessing geothermal energy requires heavy equipment and time to implement and may be geographically constrained to areas with easy access to geothermal sources, making it less attractive for early missions. Implementation of geothermal technologies would require a separate power source for the robotic drilling and regolith-moving required to access the heat sources before the crew even arrives.

Fuel cells are often proposed, but they do not trade well for mass because they either require landed reactant mass or more energy and production mass to make reactants in-situ than the fuel cells provide. Biogeneration (relying on microorganisms to convert organic feedstock directly into heat or into another commodity, such as methane, that can then be used to generate power) has also been proposed as a power generating technology option. However, the introduction of microorganisms may be complicated by planetary protection constraints. Furthermore, additional safety/processing measures may be needed if feedstock/biomass replenishment involves use of Martian soil, due to the presence of perchlorates or other chemicals and their byproducts.

Regardless of the power source selected, it should be noted that multiple power systems could be integrated as needed to support higher power needs. This would allow the power system to be tailored to a specific mission, as more modest initial efforts evolve into more ambitious exploration.

The Moon as a Testbed for Mars

The closer proximity of the Moon offers an excellent opportunity to demonstrate candidate Mars surface power generation technologies with reduced consequences of failure. Lunar surface systems designed to be extensible to Mars would need to account for the environmental differences, including Mars' low-pressure carbon-dioxide atmosphere, increased gravity, shorter day/night cycle, reduced solar insolation, wind loads, dust storms, and increased distance from Earth that results in longer round-trip communication times.

The challenge is to ensure that lunar power generation systems remain Mars-forward without adding significant cost or complexity to either the lunar or Mars missions. Solar and fission surface power technology demonstrations could serve as pathfinders for power system launch, landing, autonomous deployment, maintenance, and sustained operations in challenging and dynamic environments.

Summary

Regardless of mission type, stay duration, or surface exploration objectives, human missions to Mars will require abundant, reliable surface power. Stationary power systems that produce at least ten kilowatts day and night, in varying weather conditions, will be needed for human ascent vehicles, habitats, propellant conditioning or manufacturing plants, and surface exploration activities.

NASA is working to advance the technology readiness of a range of surface power generation technologies and mitigate performance challenges that some of these options would have in the Mars environment. An overarching objective is to demonstrate the technologies in relevant mission environments to verify performance and functionality.

Power needs for humans operating on the Moon will have some commonality with Mars operations, opening up the possibility of common power technologies if strategic engineering choices are made and proper consideration is given to the different environments. Where practical, demonstrations can be performed directly on the Moon to gain operating experience on systems that will later be used on Mars.

Key Take-Aways

Safety-critical human needs on the surface of Mars pose additional challenges, such as higher availability over longer periods of time, versus robotic Mars or human lunar surface missions.

The minimum practical power level required for even a short-duration, two-crew, human Mars surface mission is about ten kW.

Maximum required power levels could approach MW class for very in-situ resource utilization-intensive architectures.

The Mars surface power generation technology selected for the initial human Mars segment must accommodate both anticipated operational needs and the unique challenges of the Mars environment, with limited repair or replacement options.

The Artemis missions offer an opportunity to test safety-critical Mars surface power generation technologies and operations on the Moon to reduce risk for later Mars crews.

Reference

1. NASA Procedural Requirement 8715.24, Chapter 1, https://nodis3.gsfc.nasa.gov/displayDir.cfm?Internal_ID=N_PR_8715_0024_&page_name=Chapter1

Key Mars
Architecture Decisions

Introduction

As noted in the 2022 Architecture Concept Review Systems Analysis of Architecture Drivers white paper, exploration architectures are heavily influenced by the order in which driving questions are answered. Decisions in one part of the architecture will ripple through other parts of the architecture and beyond, often in ways that are not intuitively obvious.

Making one key decision before fully understanding the cascading impacts of that decision across the end-to-end architecture can limit the architecture's flexibility or utility. The essential question is: of all the important decisions to be made, which should be decided first?

The practical utility of this approach is to understand which decisions lay in the critical path of others. To make good choices, it is critical to visualize and manage the complex web of interrelated decisions and their flow-down impacts. This approach allows for deliberate and informed progress.

Ensuring the flow-down impacts of far-reaching decisions are carefully traced, assessed, and weighed will help NASA make lasting decisions that have the most flexibility and value. This is a critical factor in the effort as once these and other priority decisions are made they have lasting impact on the architecture. Subsequent changes will be costly in both time and money given the long timelines for development of new human capabilities (5 to 15 years, similar to aircraft).

This white paper describes the initial set of human Mars decisions that the agency has identified as high-priority architectural drivers.

Mapping Key Architecture Decisions

A "key" architecture decision is defined as a decision whose outcome so profoundly influences the architecture that it requires very high-level review. For example, deciding how many crew members an architecture must accommodate influences virtually every aspect of the architecture. It requires high-level consideration and consensus between multiple programs and projects.

An example at the other end of the spectrum is deciding handrail color or style. Even though the decision may affect many elements, it is best categorized as an engineering decision that will not require the same level of scrutiny.

NASA architecture teams have developed a systems engineering-driven process to:

1. identify key architecture decisions needed,
2. determine relationships between decisions (including dependencies and flow-down impacts),
3. and develop a recommended logical order in which to make these decisions.

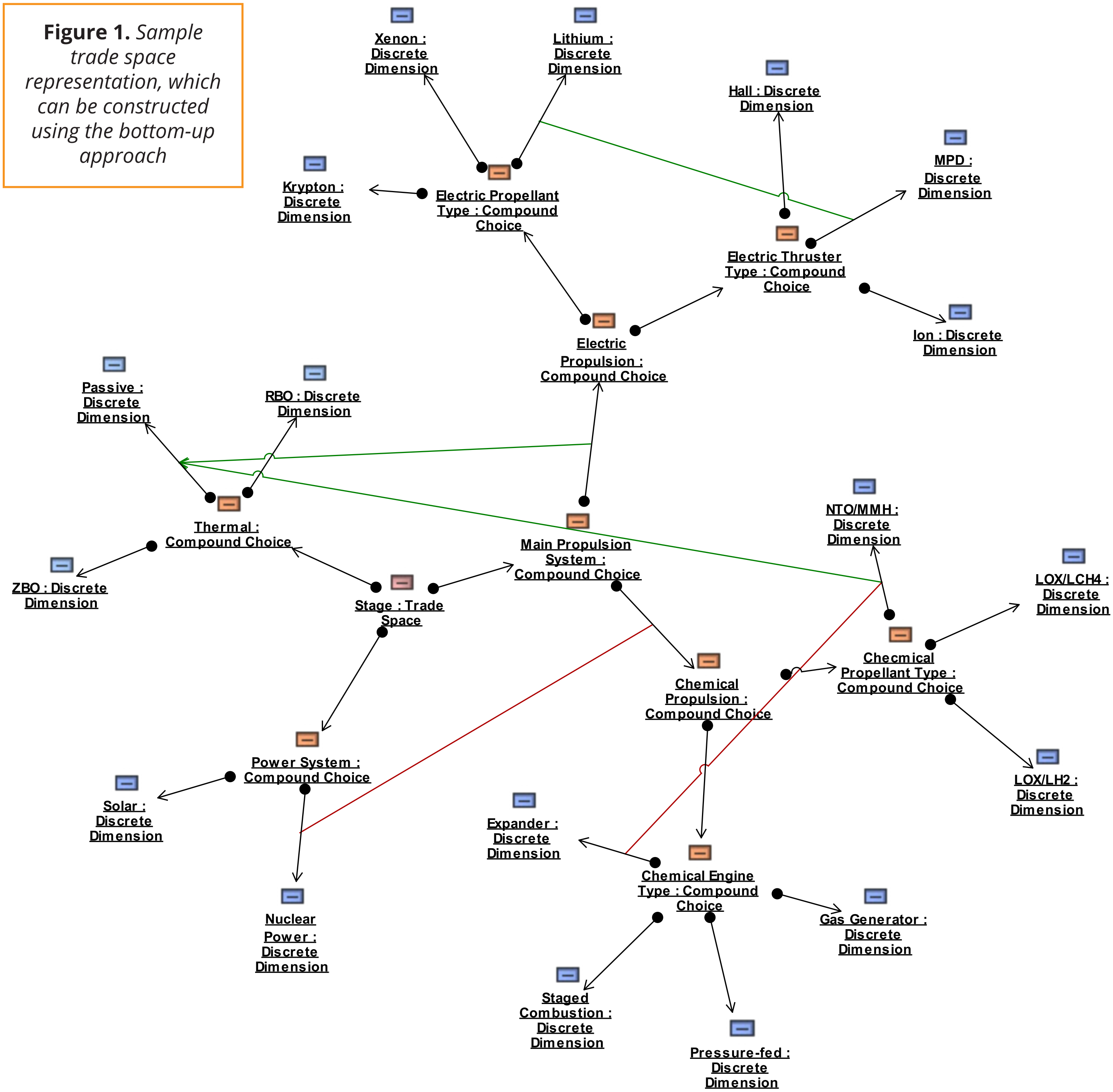
NASA is developing a model-based environment to manage this complex web of information. The process and rationale are described in the Exploration Systems Development Mission Directorate's [Moon to Mars Architecture Definition Document], Section 2.3.1 Key Mars Architecture Decision Drivers.

To develop the catalog of key Mars architecture decisions, NASA subject matter experts have begun a bottom-up review of heritage Mars architecture studies. Analyzing decades of documents, these experts identified the most influential factors in designing the initial human exploration campaign for Mars.

Next, they began decomposing the agency's blueprint objectives for exploration using a top-down approach. This resulted in use cases and functions that can then be mapped to needed architecture decisions.

Together, these two approaches provided more thorough insight, simultaneously helping refine objectives, uses cases, and functions. The resulting initial analysis — which is still ongoing

Figure 1. *Sample trade space representation, which can be constructed using the bottom-up approach*



— identified nearly 100 candidate key decisions for the Mars architecture, though the count was slightly reduced during subsequent agency-wide review and refinement.

As part of this effort, NASA also developed an initial model of architecture decision relationships. Through the frequency or dependency linkages illustrated in Figure 1, the agency extracted seven key decisions for priority analysis.

The seven decisions presented here represent NASA's initial focus for architecture integration efforts for an initial human exploration campaign for Mars. The complete model — including linkages to remaining lunar architecture decisions — continues to be developed and refined.

Seven Priority Human Mars Architecture Decisions

NASA's initial modeling effort isolated seven key human Mars architecture decisions, detailed below and shown in Figure 2. These are the recommended starting point for planning the initial human exploration campaign for Mars.

While the agency will prioritize these seven decisions first, analysis and mapping of the remaining catalog of key architecture decisions will continue in parallel. NASA

PRIORITY HUMAN MARS ARCHITECTURE DECISIONS

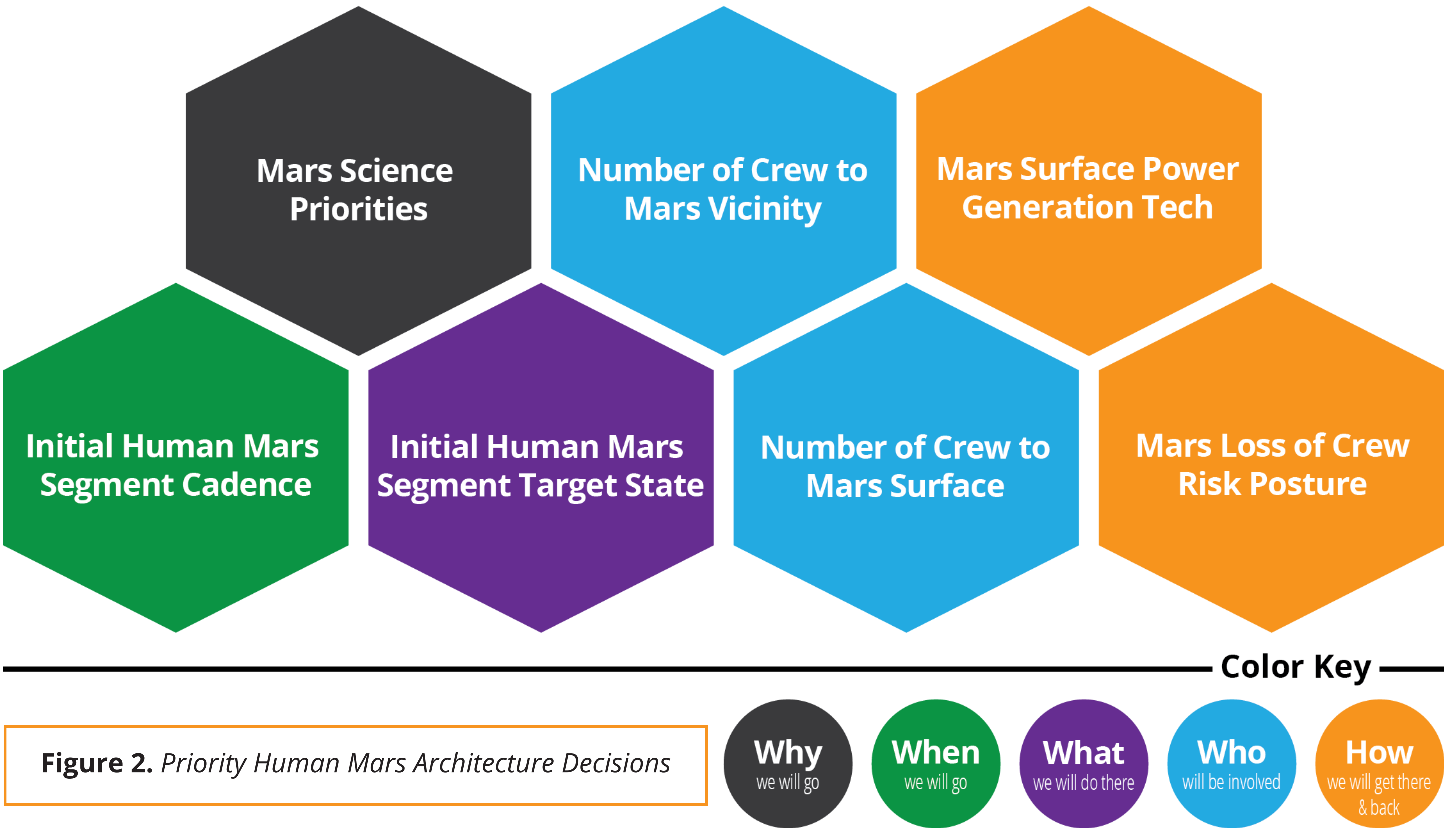


Figure 2. *Priority Human Mars Architecture Decisions*

will report progress and results at annual Architecture Concept Reviews and document them in yearly revisions to the Moon to Mars Architecture Definition Document.

Human Mars Mission Science Priorities

NASA's Moon to Mars strategy identifies science as one of three pillars upon which the agency's blueprint for sustained human exploration throughout the solar system is built. As a foundational aspiration, it can trigger the cycle of national capability and inspiration and build the value system of human exploration upon benefit to humanity. The blueprint identifies objectives in five different science disciplines:

- Lunar/planetary science
- Heliophysics science
- Human and biological science
- Physics/physical science
- Applied science

Accomplishing any portion of these objectives will require resources in virtually all aspects of the mission, including crew time, dedicated payload mass delivered to the surface, dedicated payload mass returned from the surface, communication throughput, and power. Arguably, the science conducted on the surface of Mars — at the farthest end of the human transportation and communications systems in consideration through the next decade — will have the greatest impact on the scope and scale of the architecture. Therefore, science priorities warrant the earliest possible attention.

Recent history demonstrates the importance of making this decision earlier rather than later. NASA's Artemis exploration campaign was directed to establish initial operations in the lunar South Pole region, with a focus on acquiring volatile resources thought to be found there. That limited focus may be incompatible with high-priority lunar science objectives uniquely addressed at other locations.

Establishing foundational science priorities built on broad input from the science community early in the architecture definition process may help mitigate disruption or delay to implementation of an initial human exploration campaign for Mars.

Initial Human Mars Segment Target State

A decision about the vision — or "target state" — for NASA's initial human exploration campaign for Mars is fundamental to developing an architecture that enables that vision. Architecture elements and concepts of operation will vary greatly depending on the desired end state.

For example, a series of focused science exploration missions to different landing sites would favor one architecture. Establishing a permanent, fixed base from which astronauts could conduct many surface missions supporting diverse and evolving exploration activities would favor a very different architecture.

Note that the scope of this key decision is limited to defining a vision for the initial Humans to Mars campaign segment. A separate decision will define subsequent human Mars campaign segments. The ideal end state for the vision is an architecture that meets NASA's highest priority objectives, with flexibility to expand to meet new needs or goals as they emerge.

Initial Human Mars Segment Mission Cadence

The initial state for human exploration of Mars will establish the "right" for "architecting from the right," but other questions remain:

- How many unique missions are necessary during the initial segment? (These could include robotic science, cargo delivery, or precursor demonstration missions.)
- Will there be crewed orbital or fly-by precursor missions to Mars, or will the first crewed mission land on the surface of the Red Planet?
- What additional resources are needed to balance the cadence of initial Mars missions with ongoing near-Earth and lunar surface operations?

Historically, human exploration spaceflight programs have established a campaign of test flights, demonstrations, and crewed missions that build up to a desired end state. Depictions of these gradual buildups can aid stakeholders in strategic planning and investment forecasting for the initial human exploration campaign for Mars.

Mars Loss of Crew Risk Posture

Robotic exploration projects typically establish a loss of mission risk posture, but human spaceflight programs must also develop an understanding of the overall loss of crew risk. Loss of crew risk posture is a useful guidepost in making risk-informed architecture decisions. For example, whether to prioritize technologies that enable faster round-trip human missions as one means to mitigate crew health and performance concerns.

As the architecture becomes more defined, a formal agency-level safety reporting threshold will be established for each design reference mission to achieve human rating certification. However, establishing a risk posture guidepost early in the architecture development process will help avoid disruptions and reworks during the later certification phase.

Number of Crew to Mars Surface per Mission

Crew complement is the most common study constraint across all architectures and elements. Crew complement selection has implications for habitable vehicle and element volume, life support system design, and crew support systems for health and performance (such as medical, exercise, and food systems). It also has ramifications for logistics needs (including science and mission utilization, food, clothing, medical supplies, etc.), which inform campaign launches and cadences.

Operationally, crew complement helps establish an upper limit for Mars entry, descent, landing, and ascent vehicle sizing (with flow-down impacts to ascent propellant management, including Mars surface infrastructure needs). It also helps establish a lower limit for crew availability to perform systems monitoring, maintenance and troubleshooting; science and utilization (particularly during surface extra-vehicular activities); and inspirational engagements with the public. The unique communications challenges at Mars — an environment where real-time communication with Earth is not possible — also have implications for task management and contingency responsiveness of a given crew complement during critical operations.

Number of Crew to Mars Vicinity per Mission

A companion to the Mars surface crew complement decision is deciding the total crew complement to Mars vicinity. This decision will have some similar considerations to defining crew complement to the surface, but also some unique constraint drivers.

The number of crew to the vicinity of the Red Planet will have implications for Earth ascent and descent, Mars transit vehicle habitable volume, crew support systems sizing, and logistics manifesting. This decision may also influence Mars capture and parking orbit operations, with flow-down implications for task management and contingency response. For example, in "split crew" architectures, some crew might remain in Mars orbit while others descend and work on the surface, changing the crew's physical availability to perform these functions.

Primary Mars Surface Power Generation Technology

The scope of human exploration on Mars will depend largely on the amount of energy available. That energy will power crew life support systems, support surface element keep-alive functions, and make, move, or maintain critical ascent vehicle propellants.

Solar energy has long been a reliable choice for in-space power applications. However, recent robotic science mission experience has brought solar power risks for Mars surface missions into sharper focus, particularly given the loss of crew risk if the surface power system were to fail during a human expedition with limited mission abort options.

This particular architecture decision is limited in scope to power generation technique. Power load sizing and distribution technology selections are cataloged as separate decisions, though interdependencies with those decisions must be factored into power generation decision analyses. The narrowing window of opportunity to infuse Mars-forward considerations into lunar surface power implementation decisions for Artemis make this a timely activity.

Future Work

During upcoming strategic analysis cycles, NASA architecture teams will continue to refine the modeling environment, assess various options within the solution space, and prioritize remaining decisions for the initial human exploration campaign for Mars. As the bottom-up and top-down identification processes continue, additional needed decisions may be identified. Linkages to decisions for lunar exploration campaign segments that have not yet been made will be developed, analyzed, and prioritized. This insight will enable an informed and methodical approach to address the needs of the multi-decadal vision that is the Moon to Mars Objectives.

Conclusions

Developing architectures to enable human exploration of the solar system will require hundreds of individual decisions by many different decision authorities across the agency. All of these decisions will be important, but there is a class of decisions that so profoundly influences the entire end-to-end architecture as to warrant the highest level of scrutiny. Ensuring the integrated impacts of far-reaching decisions are carefully traced, assessed, and weighed will help decision authorities make lasting decisions that are resistant to implementation delays, disruptions, or costly relitigation.

Through a methodical process, NASA has identified a set of seven Mars architecture decisions to start with. However, the agency will continue to define and map the full catalog of key decisions, reporting progress at annual Architecture Concept Reviews and updating the Architecture Definition Document with architecture decisions as they are made.

Key Take-Aways

The order in which key decisions are made heavily influences exploration architectures. Every decision is important, but not every decision can be first.

NASA endeavors to establish a logical order for decision making by modeling the decision trade space for human Mars exploration. This methodology will allow decision-makers to understand the integrated impacts of each individual decision on the overarching architecture.

Of the nearly 100 Mars architecture candidate decisions identified for analysis, NASA has identified seven key decisions to focus on first.

While Mars serves as a test case for this approach, lessons learned will inform future decision-making for the Moon and subsequent human exploration enterprises.

As architecture decisions are made, updates will be reflected in NASA's Moon to Mars Architecture Definition Document.

National Aeronautics and
Space Administration

Human Health and Performance: Keeping Astronauts Safe & Productive On a Mission to Mars

Introduction

NASA has been sending humans to space for more than 60 years, confronting the essential challenge of human spaceflight: that our bodies and minds evolved to live on Earth. Living and working off our planet, and on another planet, poses unique hazards to the human system. Understanding the effects of spaceflight on human physiology, psychology, and individual and team performance is essential to keep astronauts safe and healthy as exploration moves from low-Earth orbit to deep space destinations on and around the Moon and eventually Mars.

The five main hazards of human spaceflight are space radiation, isolation and confinement, distance from Earth, altered gravity fields, and hostile/closed environments. This paper will highlight how these hazards and the risks they pose to the human system influence NASA's Moon to Mars Architecture. These hazards are not always independent from one another; like human systems, the hazards are frequently coupled and interconnected, potentially causing synergistic effects or combined impacts.

Addressing the hazards and defining solutions will require a combination of human health and performance and engineering solutions. These solutions will be balanced with acceptable risks imposed on the crew and mission parameters such as duration, vehicle designs, operational considerations, and cost.

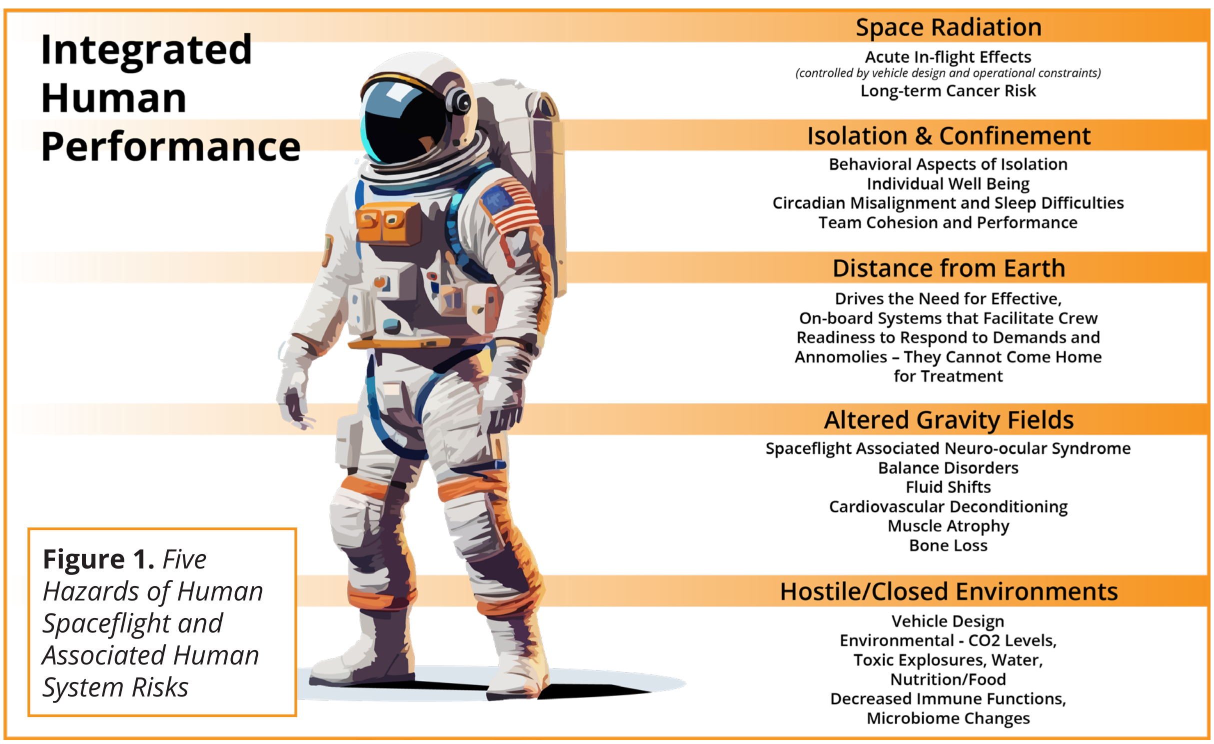


Figure 1. *Five Hazards of Human Spaceflight and Associated Human System Risks*

The following content integrates and summarizes NASA-STD-3001, NASA Spaceflight Human-System Standard Volume 1 and 2, which establishes agency standards that enable human spaceflight missions by minimizing health risks, providing vehicle design parameters, and enabling the performance of flight and ground crew. Applicability and tailoring of standards are determined based on each program's mission profile and procurement strategy.

Space Radiation

On a Mars mission, crew members will experience accumulated ionizing radiation exposure from galactic cosmic radiation and solar particle events. Solar particle events can expose astronauts to sudden increases in radiation, but the probability of a large event that would cause acute syndromes such as nausea and fatigue is extremely low (approximately 1 in 1,000). Shielding of spacecraft and habitats is effective against solar particle events, but only mitigates galactic cosmic radiation exposure by approximately 7–15 percent.

Deep space radiation exposure is a mitigated in-mission risk for acute radiation sickness. The consequences of spaceflight radiation exposure are an increased risk of cancer incidence and death later in life (post-mission), along with increased risk of cardiovascular disease.

The overall increase in cancer mortality for an average weight, non-smoking astronaut would increase from a probability of 15 percent over a lifetime to approximately 20 percent after a 1,000-day Mars trip (which is a 33 percent increase in lifetime mortality risk). Comparatively, an American who is overweight, drinks alcohol, consumes an average diet, and lives a less active lifestyle than a typical astronaut has an approximately 21 percent probability of dying from cancer.

For comparison, occupational controls for terrestrial radiation workers — such as personnel working at nuclear power plants or medical personnel using x-ray equipment — require radiation exposure to incur less than a 0.5 percent increase in mortality risk per year; nominally, exposure is controlled to incur less than a 0.1 percent increase in mortality risk per year.

Transit vehicles and habitat design guidance to minimize radiation exposure should consider the following factors:

- **Transit time and mission timing:** Minimize the total transit time between the planets to reduce the crew's radiation exposure, and plan transits during solar maximum to minimize galactic cosmic radiation exposure.
- **Engineering countermeasures:** Provide shielding from solar particle events using existing/planned vehicle mass. Use of consumables, including environmental control and life support system water/gray water, should be considered for solar particle event protection in lieu of polyethylene.
- **Optimized vehicle design and shielding materials:** Use existing mass to increase global cosmic radiation shielding to approximately 7–15 percent.
- **Monitoring/notification:** Provide onboard capabilities to detect, monitor, and characterize the radiation environment.

Isolation and Confinement

Future exploration missions will involve humans traveling further from Earth for longer mission durations. These missions will likely necessitate prolonged periods of isolation and confinement that pose a greater risk for behavioral health and performance. These hazards could lead to:

1. Adverse cognitive or behavioral conditions affecting crew health and performance during the mission.
2. The development of psychiatric disorders if adverse behavioral health conditions are undetected or inadequately mitigated.
3. Long-term health consequences, including late-emerging cognitive and behavioral changes.

Transit vehicles and habitat design guidance to mitigate various psychological stressors should consider the following factors:

- **Personal/private space:** Provide separate, individual sleeping/personal quarters with auditory isolation and physical separation (if possible) for each crew member. Private spaces separate from common spaces, social areas, and congested movement paths are preferred.
- **Workspace:** Allocate adequate volume and resources to accommodate everyone's work and activities (e.g., science, laboratory equipment, electronic curriculum).
- **Window:** Provide at least one window for direct viewing outside of the vehicle.
- **Cabin environmental controls:** Ensure each crew member can control cabin temperature, ventilation, lighting, humidity, and noise by placing individual controls and distribution vents in crew quarters and at workstations.
- **Communication with home:** Each private quarter should include communication systems that facilitate multiple modes of communication.
- **Crew composition:** Characteristics of expected range of crew composition (including team size, gender makeup, job roles, and cultural backgrounds), which are established before the mission.
- **Team coordination and collaboration:** Provide common areas with enough volume for the team to gather for recreation and dining, including screen access for communal viewing.
- **Human factors and habitation:** Spacecraft designers should use human-centric approaches to create optimal workload, habitable volume, and layout, ensuring adequate movement pathways and volume envelopes and access to rails and harnesses.

Distance from Earth

Mars is, on average, 140 million miles from Earth, with a one-way communication delay of up to 22 minutes. This distance will require astronauts to solve problems and identify solutions as a team, without immediate help from NASA's mission control.

As distance from Earth increases, spaceflight crews will, by necessity, become increasingly independent from mission control, and more dependent on their vehicle and logistics. This elevates the need for effective on-board systems that enable the crew to respond to demands and anomalies that may acutely arise.

This autonomy (or "Earth independence") must enable the astronauts to maintain, debug, and repair the vehicle. It must also allow them to monitor the state of their own health and wellbeing by accessing and using medical information in real-time operations and use decision support tools to reduce cognitive burden. Current plans entail years of training to prepare astronauts for such missions, increasing the risk that not all training will be retained (and/or retrievable).

Transit vehicles, habitats, and operational guidance to enable crew and vehicle autonomy should consider the following factors:

- **Integrated data architecture/decision support tools:** Implement a vehicle-integrated data architecture and decision support tools that enable crew to make decisions independently of immediate ground support.
- **Robust on-board medical capabilities:** Provide advanced prevention, diagnostic, treatment, and rehabilitation modalities.
- **Automation/robotic systems and human interaction:** Human operators need to maintain situational awareness to work effectively with automation.
- **Food and nutrition:** Provide safe, nutritious, and palatable food with sufficient calories, micronutrients, and macronutrients. Consider shelf life if food will be sent ahead of crew.
- **Maintainability:** Design for maintainability, with system-level optimization for parts and ergonomics. Consider tools and information as part of the design to consume minimal crew time.
- **Crew training:** Provide adaptable, in-mission training capabilities for crew.

Altered Gravity Fields

Astronauts will encounter different gravity fields on a Mars mission. On the multi-month trek between the planets, crews will be weightless in microgravity. While living and working on Mars, crews will have to adapt to a partial gravity environment (three-eighths of Earth's gravity), and upon returning home, crews will have to readapt to Earth's gravity. Landing a spacecraft on Mars could be challenging as astronauts adjust to partial gravity.

In addition to sensorimotor disruptions, crew members may have difficulty maintaining their blood pressure while standing, potentially leading to lightheadedness and fainting. Additionally, musculoskeletal unloading in microgravity will lead to decreased aerobic capacity, muscle strength, and bone quality and density (weight-bearing bones are estimated to lose about 1–1.5 percent mineral density per month spent in microgravity, which may lead to long-term changes in bone that increase fracture risk). Fluids in the body also shift upward to the head in microgravity, resulting in structural and functional changes to the eye and increases in the brain ventricular and perivascular volumes that can develop in flight and persist after flight (Spaceflight Associated Neuro-ocular Syndrome [SANS]).

Transit vehicle design, habitat design guidance, and egress/ingress/return considerations to mitigate various physiologic effects should consider the following factors:

- **Exercise:** Provide sufficient volume, mass allocation, and vehicle vibrational damping for physiological countermeasures.
- **Sensorimotor/balance:** Provide for in-flight sensorimotor countermeasures adaptation training to improve astronauts' performance. Operational timelines should reduce the number of critical activities for a defined period after a gravity transition to ensure crew performance, safety, and mission success. Extravehicular activity suit and rover design considerations can also be applied to address sensorimotor functioning.
- **SANS:** Provide sufficient volume and mass allocations for pharmaceutical or mechanical countermeasures.
- **Acceleration and dynamic loads:** Design the vehicle's acceleration/deceleration profiles and dynamic phases of flight for deconditioned crew members with reduced abilities (for both nominal/automated operations and manual crew control).
- **Anthropometrics:** Consider all operational gravity fields and environments, designing habitable volumes that ensure all crewmembers can perform any planned tasks efficiently and effectively.

Hostile/Closed Environments

The ecosystem inside habitats and spacecraft is crucial in everyday astronaut life. In space, enclosed environments (including vehicles and suits) do not have the benefit of natural CO2 removal, relying instead on CO2 removal equipment to help regulate CO2 levels and decrease the risk of negative consequences of elevated CO2 exposure. Additionally, lunar and Martian dust exposure could lead to serious health effects to the crew, such as respiratory, cardiopulmonary, ocular, or dermal harm.

To ensure environmental adequacy, transit vehicles, habitat design, and extravehicular activity planning guidance should consider the following factors:

- **Environmental control and life support system:** Provide clean air and adequate water quantities for consumption and hygiene. Manage air and water quality, waste, atmospheric parameters, and emergency response systems.
- **Countermeasures:** Mitigate the risk of infectious disease (viral and bacterial) and alterations to immunity (due to spaceflight stressors) through implementation of a pre-flight crew health stabilization program.

- **Atmospheric pressures/composition and materials/ flammability:** Consider differences in flammability in different atmospheric pressures and compositions. Vehicle and suit design should also incorporate on-board treatment of decompression sickness.
- **Dust mitigation:** Provide adequate air filtration systems to meet existing standards for dust exposure. Consider an airlock for ingress/egress to separate the vehicle hatch from the habitation area to further prevent contamination. Protect extravehicular activity suit joints and closures functions to prevent breaches.

Key Take-Aways

The human system is being considered early in vehicle design phases and operations for Mars architecture development. The architecture recognizes the five primary hazards of human spaceflight (space radiation, isolation and confinement, distance from earth, altered gravity fields, and hostile/closed environments) and balances risks with cost and design parameters. Missions may be comprised of consecutive segments that occur in different vehicles at different locations in space with varying distances from Earth and that last for different durations. However, the cumulative exposure to the five hazards over the entire mission duration needs to be considered to protect human health and performance. Shorter transit times to Mars would ameliorate many of the human system risks. Mars missions will require crew and vehicle autonomy, which will be a significant paradigm shift from current low-Earth orbit missions.

Additional Reading

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Round-Trip Mars Mission Mass Challenges

Introduction

As noted in the 2022 Architecture Concept Review "Mars Transportation" white paper, the distance between Earth and Mars changes constantly as the two planets revolve around the Sun. Regardless of their relative positions, traveling to Mars requires significantly more energy than lunar missions. However, the distance between the planets is only part of the story. This white paper explains how gravity wells, combined with the distance and desired transit duration between them, serve as a mass, and potentially cost, multiplier for a round-trip human Mars mission.

Escaping from a Gravity Well

A gravity well is one way to visualize the gravitational pull exerted by a large body in space. The "depth," or strength, of a given gravity well is a function of the planetary body's mass, with the bottom of the well terminating on the body's surface. For example, Mars is smaller and less massive than Earth, so Mars' gravity well is shallower than Earth's gravity well; the Moon is even less massive than Mars, so the Moon's gravity well is much shallower than either Earth's or Mars' gravity wells, as depicted in Figure 1.

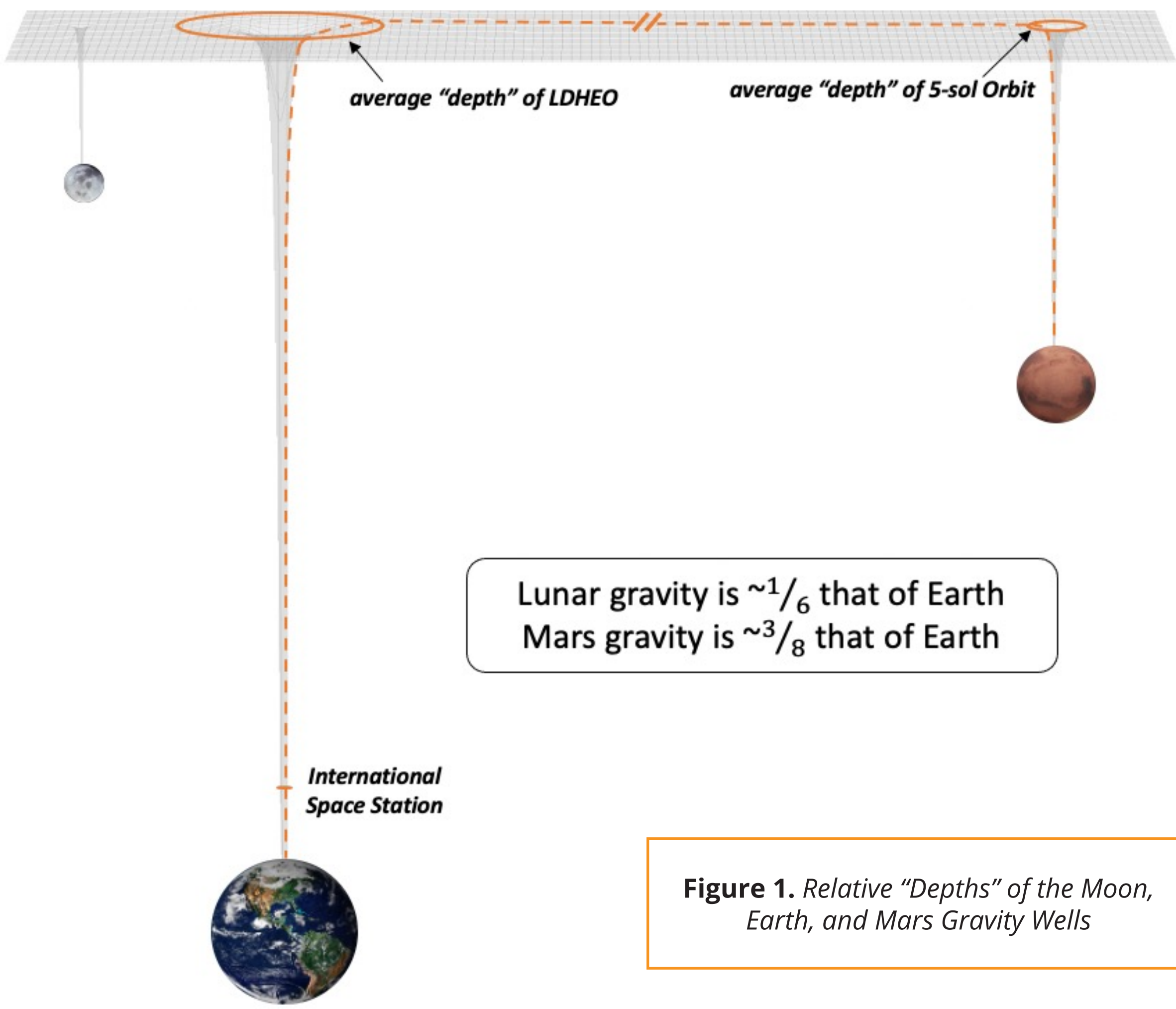


Figure 1. *Relative "Depths" of the Moon, Earth, and Mars Gravity Wells*

Gravity wells help visualize part of the mass challenge that a round-trip human Mars mission poses. Most people can appreciate that climbing up a taller hill (or climbing out of a very deep well) requires more physical exertion than climbing up a smaller hill (or climbing out of a very shallow well). Consider the exertion required to "climb" from a planetary body's surface to orbit, but with exertion measured in kilograms (kg) of rocket engines and propellant instead of calories burned.

For example, visualizing the depth of Earth's gravity well versus the Moon's helps explain why Apollo astronauts required the large Saturn V rocket just to escape Earth's gravity well and reach the Moon, but could escape from the Moon's gravity well and return to Earth with a much, much smaller vehicle.

Ascent from the surface of a gravitational body not only requires the thrust necessary to counteract gravity and ascend to a target altitude, but also that the spacecraft match the orbital velocity of the target orbit. Proximity to a gravitational body determines the gravitational pull that body exerts on the spacecraft.

For circular orbits, which have a near-constant orbital altitude, the gravitational pull will be constant. For elliptical orbits, the gravitational pull will vary over the course of the orbit as the distance between the spacecraft and gravitational body changes. Highly elliptical orbits, which are extremely elongated (e.g., lunar-distance high-Earth orbit (LDHEO) or the 5-sol Mars orbit) spend a significant percentage of their orbital period at distances far from the gravitational body, meaning that the "average" depth of these orbits is near the top of the gravity well. Orbits near the top of the gravity well generally require less effort to escape than orbits closer to the bottom of the well.

However, depth in a gravity well is not the only factor to consider when evaluating the relative difficulty of escaping a gravitational body. Escaping requires a spacecraft to achieve enough kinetic energy — the energy due to its orbital velocity — to overcome the gravitational pull. Like the gravitational pull, orbital velocity increases and decreases over the course of a period in an elliptical orbit. Although gravitational pull is reduced at farther distances, departure burns from elliptical orbits are typically done near closest approach, where the difference between the kinetic energy of the spacecraft and the kinetic energy required to escape is at a minimum.

Interplanetary Transit and Capture

Reaching Mars requires not only the energy to climb out of Earth's gravity but additional energy to transit the distance between Earth and Mars. While Figure 1 is useful for visualizing the relative "depths" of gravity wells, it does not capture the changing distance between gravity wells.

Both Earth and Mars orbit the Sun, but travel at different velocities, so the distance between them is constantly changing. Over the course of their 780-day synodic period, this separation varies by between 56 and 400 million kilometers, but a spacecraft cannot simply travel in a straight line between them. Instead, a spacecraft must traverse in parabolic paths (Figure 2) shaped by the Sun's gravity and the desired transit time between Earth and Mars. The transit time between the planets determines the distance traveled and the amount of energy that must be expended to accomplish the mission. Fast transits between Earth's and Mars' gravity wells can be more expensive (in terms of energy) than escaping their respective gravity wells.

In addition to distance, the relative velocity of the planets, mission duration, and orbital stay time all influence the interplanetary energy required to reach Mars. A vehicle departing Earth must expend energy to accelerate toward Mars — and then expend more energy to match Mars' speed once it arrives at Mars vicinity. A vehicle must slow down as it gets closer to a planet before it can "fall" into the planet's gravity well. If the vehicle is going too fast, it can easily "skip" over the gravity well, much like a fast-moving golf ball skipping over a golf hole.

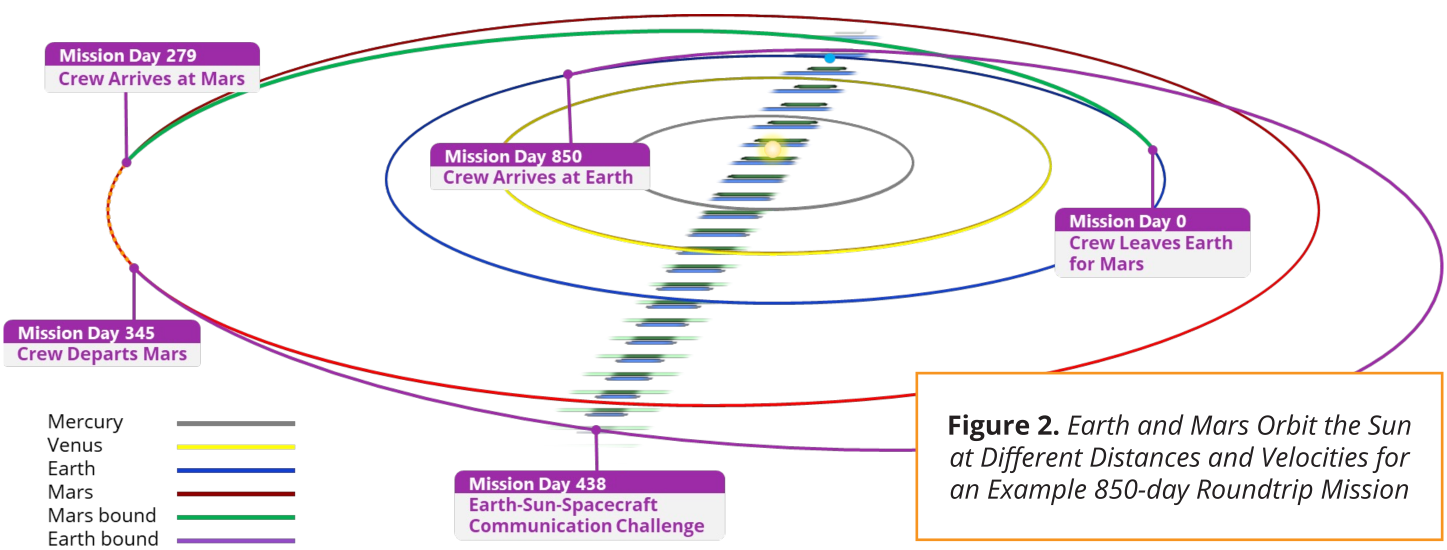


Figure 2. *Earth and Mars Orbit the Sun at Different Distances and Velocities for an Example 850-day Roundtrip Mission*

How fast a spacecraft travels is a function of the desired transit time between planets; faster requires more transit energy but reduces trip time. For the sake of minimizing crew exposure to the space environment, faster is better (for the crew), but faster comes with an enormous energy penalty that results in increased propulsion system and propellant mass.

Minimum-energy missions utilize optimal planetary alignment for each leg of the interplanetary transit, resulting in a long (300 days or longer) loiter period at Mars and a round-trip mission duration of about 3 years. Trip time can be reduced by optimizing planetary alignment for only one leg of the mission, paired with a short loiter period at Mars, for a round-trip duration on the order of about 2 years, but at the expense of additional interplanetary energy expended on the non-optimal leg.

Shortening transit times between bodies generally increases the propulsive energy the transit vehicle must deliver. Short transits require acceleration to a higher energy state and consequently approach their target with higher excess velocity. Longer transits provide more time to obtain minimum energy transfers through optimal planetary alignment. The 2022 Architecture Concept Review "Mars Transportation" white paper used an 850-day round-trip mission (Figure 2) to compare several transportation options.

The energy required to capture into a body's gravity well is generally applied quickly at the point of closest approach to reduce the relative velocity of the capturing spacecraft. Although the body continues to exert its gravitational force on the spacecraft while in orbit, pulling it toward the surface, the translational velocity of the spacecraft keeps it in orbit. A de-orbit burn to arrest this translational velocity and slow down further allows the body's gravitational force to pull the spacecraft down to the surface. Typically, crewed and uncrewed landing systems remove orbital energy following the de-orbit burn to maintain a safe landing velocity.

One Way v. Round-Trip Missions

All robotic Mars missions to date have been one-way, so they have only had to exert enough energy to climb out of Earth's gravity well and push the payload to Mars vicinity. Once the robotic payloads arrived at Mars, they "fell" into the Mars gravity well, often bypassing orbit capture, with additional energy expended to slow down for a soft landing. Robotic missions are afforded the option to bypass orbit capture and decelerate while following a direct path to the surface because they can withstand more force during the "fall" into Mars' gravity well and they typically do not have to rendezvous with anything in Mars orbit prior to descending to the surface.

The first part of a round-trip human Mars mission is similar to a one-way robotic mission: the crewed vehicle and cargo need to escape Earth's gravity well, transit to Mars, capture into the Mars gravity well, and then de-orbit to initiate the "fall" to the Martian surface — with a little bit more energy expended to slow down for a softer landing on the Martian surface. However, unlike the one-way robotic missions, the humans need to return to Earth. To do this, they will need enough energy to climb back out of the Mars gravity well, push the crew, their return cargo, and their vehicle back to Earth, and then capture back into Earth's gravity well. This means more than double the amount of energy is needed for a human Mars surface mission compared to a one-way robotic mission.

Figure 3 shows the mass impact of traversing 1 kg of payload from Earth launch through a full round-trip mission versus delivering 1 kg of payload from Earth launch to the Martian surface. For the round-trip mission, ascent from the Martian surface is a mass driver that ripples through the earlier stages of the mission.

Gear Ratios

The mass required to launch any given payload out of Earth's gravity well, transport it to Mars, slow it down, descend, and land it on Mars is a mass multiplier, sometimes called a "gear ratio." This ratio provides a numerical representation of climbing in and out of planetary gravity wells. Gear ratio is defined as the change in the initial mass of the vehicle when a unit of payload (inert mass) is added. In other words, how much more mass is needed to deliver 1 additional kg of mass to a given point in the journey.

The relationship between the initial and final mass of a spacecraft is a function of ΔV ("delta V," the change in the velocity of the spacecraft to modify its kinetic energy), specific impulse of the propulsion system (how efficiently the propellant is converted into thrust), and propellant mass fraction (proportion of the vehicle mass that is propellant). Gear ratio will grow exponentially as the propellant mass fraction increases. Missions with higher energy requirements, like short-duration crewed surface missions to Mars, will have higher propellant mass fractions, and therefore higher gear ratios, than a Mars science payload performing a one-way, conjunction-class transit.

Gear ratio can be a convenient back-of-the-envelope multiplication factor to estimate propellant requirements or provide insight into the relative difficulty of a mission. A gear ratio will provide more straightforward insight for missions that utilize a single vehicle than it would for a complex mission with several propulsive elements.

Many architectures split propulsive responsibility between several elements to maintain their individual masses within feasible limits. For multi-element architectures, gear ratio applicability is limited to the mission phases for which an element is actively providing the propulsion.

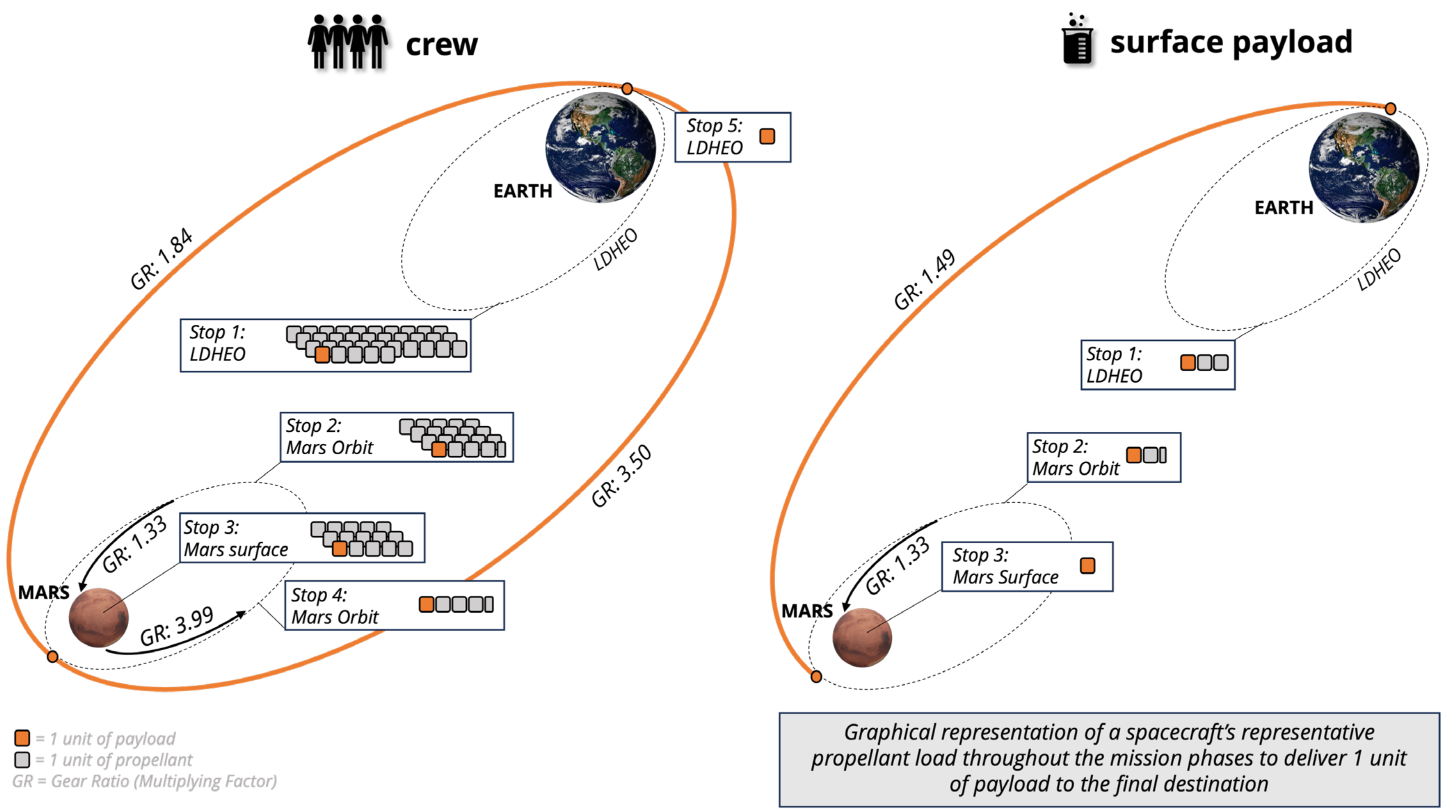


Figure 3. *Mass Impact of Delivering 1 kg of Payload Round-Trip vs. One-Way*

Additionally, many architecture elements duplicate mission phases, such as a cargo vehicle pre-positioning a lander and a later crewed vehicle that would both individually complete Earth departure and Mars orbit capture, leading to a compounding effect when looking for a whole architecture perspective.

If the mission involves manufacturing Mars ascent propellant on Mars, that propellant is not "free." The equipment needed to manufacture Mars ascent propellant will originate on Earth, so the full "cost" of that Mars ascent propellant will have to account for the mission mass required to launch the propellant manufacturing equipment out of Earth's gravity well, push it to Mars, then slow it down at Mars so it can descend and land, adding to the gear ratio.

Although a gear ratio can give insight into how inert mass added to a spacecraft can impact mission mass, it is a highly variable value that depends on mission parameters and spacecraft performance. Different missions across an architecture can have different gear ratios, which will reflect the varying mission parameters and spacecraft characteristics necessary to accomplish different missions.

Comparing gear ratios can provide an idea of the relative propulsive difficulty required to accomplish different missions with the same propulsion system or the relative efficiency of different propulsion options when comparing them for a similar mission, such as the example 850-day round-trip mission. However, gear ratio should not be used as a stand-alone metric by which to assess architectures, as it does not convey the full scope of what an architecture is attempting to accomplish. Bringing more people or infrastructure to the surface of Mars will result in an architecture with a higher gear ratio than a science mission, but also adds capabilities to meet expanded surface objectives.

Mass Multiplier Case Study

Gear ratios can be computed for each phase of a mission and show the initial mass required to move 1 kg of payload through that phase. Multiplying gear ratios for each phase results in the full gear ratio, or mass multiplier, for a given mission.

Figure 4 provides two example cases that show the full mission gear ratio for an 1,100-day Earth-Mars round-trip mission (left) versus an 850-day Earth-Mars round-trip mission (right). For a single vehicle to complete the entire end-to-end 1,100-day mission would require approximately 10.6 kg of propellant mass for each kg completing the full round trip from LDHEO departure through return. Comparatively, an 850-day moderate-duration round-trip mission has a full mission gear ratio of approximately 34.4, about 3 times that of the 1,100-day conjunction-class mission.

When compared with the relatively small gear ratios required to land payload on the surface, these large round-trip gear ratios make using a single vehicle

Example Earth-Mars 1100-day Round-trip Mission			
Mission Phase	**ΔV**	**PMF**	**Gear Ratio (350s isp)**
LDHEO→5-sol Mars Orbit	1350 m/s	0.33	1.49
5-sol Mars Orbit→Mars Surface	1000 m/s	0.25	1.33
Mars Surface→5-sol Mars Orbit	4750 m/s	0.75	3.99
5-sol Mars Orbit→LDHEO	1000 m/s	0.25	1.33
	Mission Gear Ratio		10.6

Transit Vehicle *(2.0 GR)*

Lander or Surface Cargo *(2.0 GR)*

Mars Ascent Vehicle *(7.9 GR)*

Transit Vehicle *(6.4 GR)*

Example Earth-Mars 850-day Round-trip Mission			
Mission Phase	**ΔV**	**PMF**	**Gear Ratio (350s isp)**
LDHEO→5-sol Mars Orbit	2100 m/s	0.46	1.84
5-sol Mars Orbit→Mars Surface	1000 m/s	0.25	1.33
Mars Surface→5-sol Mars Orbit	4750 m/s	0.75	3.99
5-sol Mars Orbit→LDHEO	4300 m/s	0.71	3.50
	Mission Gear Ratio		34.43

Figure 4. *Gear Ratios for 850-Day and 1,100-Day Crewed Round-Trip Mars Missions*

without any prepositioned components (such as return propellant, a lander, or an ascent vehicle) a challenge. Mission designs frequently split the crewed mission, and its gear ratio, between multiple components to limit the mass of any one element — for example, a transit vehicle for moving between Earth and Mars gravity wells, a lander to descend to the surface, and an ascent vehicle with pre-positioned propellant to return from the Martian surface to orbit.

Key Take-Aways

Gravity well depth and the distance and desired transit time between gravity wells influence the total Earth-launched mission mass required for a particular payload.

Though it is tempting to extrapolate lunar transportation system costs to Mars applications, the Mars gravity well is deeper, and much farther away, than the Moon's gravity well, so the "cost" of a lunar architecture used at Mars cannot be directly translated without significant additional engineering analysis.

A given mission's total Earth-launched mass is often used as an analog for cost and can be useful in assessing the relative cost per kilogram of a given mission, as mission assumptions vary.

Gear ratios can provide insight into how inert mass added to a spacecraft can impact initial mass, but vary significantly based on mission parameters and spacecraft performance. They should not be used as a stand-alone metric by which to assess mission architectures, as they do not convey the full scope of what an architecture is attempting to accomplish.

Exploration Lessons from the International Space Station

Background

The International Space Station is the world's preeminent orbital microgravity platform. For more than 20 years, scientists have used the space station to conduct research into biological, physical, biomedicine, materials, and Earth and space science. Technology demonstrations aboard the space station have advanced state-of-the-art applications with benefits both on Earth and in space. The space station's redundant systems enable the crew to test multiple environmental systems simultaneously, creating a unique testbed for life support and environmental technology that will enable future exploration. Sensors deployed on the space station have validated climate models and contributed to host of new information about Earth's changing climate, while space science instruments on the orbiting laboratory have advanced our knowledge of phenomena like neutron stars and dark matter.

International Space Station crews have also been part of a critical experiment, volunteering themselves as test subjects for research into human adaptation to microgravity. These long-duration demonstrations and experiments into the joint human-and-vehicle system are enabling future human exploration of the solar system. The station will operate through 2030, continuing to offer benefits to humanity while paving the way for commercial industry to meet NASA's needs in low-Earth orbit and beyond.

The International Space Station has five major goals and has realized significant advances in each:

- Enable deep space exploration.
- Conduct research to benefit humanity.
- Foster a U.S. commercial space industry.
- Lead and enable international collaboration.
- Inspire humankind.

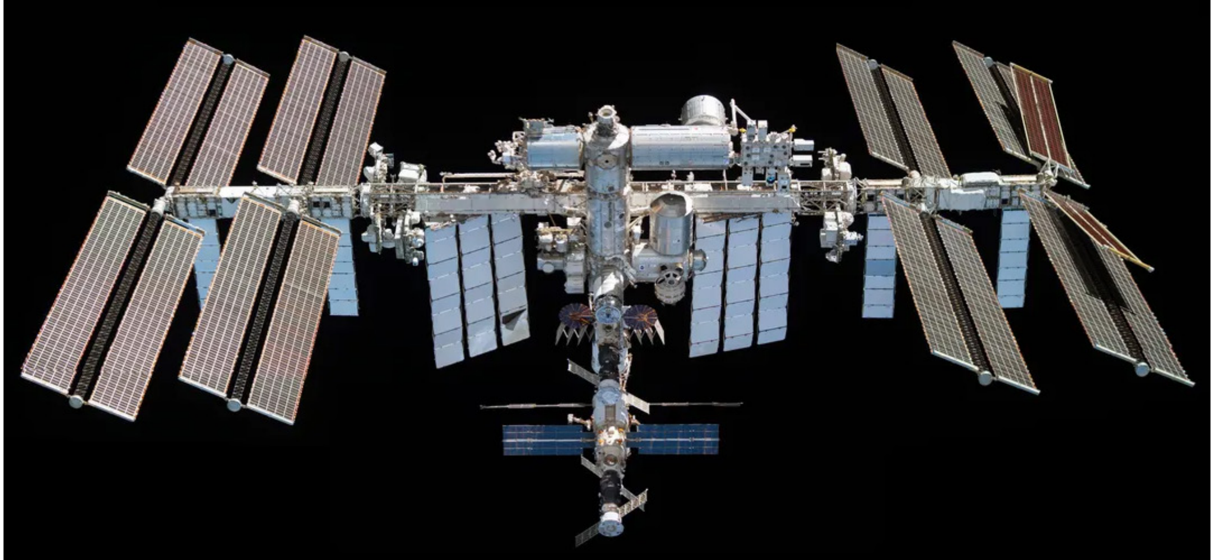


Figure 1. *This mosaic depicts the International Space Station pictured from the SpaceX Crew Dragon Endeavour during a fly around of the orbiting lab that took place following its undocking from the Harmony module's space-facing port on Nov. 8, 2021.*

The station's first decade was dedicated to on-orbit assembly. Its second was devoted to research and technology development and learning how to conduct these activities most effectively in space. The station is now in its third and most productive decade, continuing to advance research, create commercial value, and bolster global partnerships. During this period, NASA will test and validate exploration and human research technologies to support deep space exploration, continue to return medical and environmental benefits to humanity, and lay the groundwork for a commercial future in low-Earth orbit.

The space station offers a unique platform for demonstrating new technology in space, including the technologies needed for the Artemis missions to the Moon and future missions to Mars. Exploration-focused research and development on the station includes environmental control and life support systems (ECLSS), navigation, food storage systems, extravehicular activity (EVA) suits, and human research, among others. This white paper details how technology developed on the station and lessons learned from station operations enable future exploration missions.

Fly-Off Plans

The International Space Station program tracks the key technologies and human health mitigations needed for deep space exploration through a series of "fly-off" plans. These plans ensure that NASA completes all research that must be done in the low-Earth orbit environment before the end of the station's operational life, planned for 2030. The plans also account for technology demonstrations that may be started on the space station but concluded on commercial low-Earth orbit destinations after the station's retirement.

Environmental Control and Life Support Systems

Since 2009, the regenerative ECLSS aboard the International Space Station has been tested and upgraded into the Exploration ECLSS, intended to support long-duration missions beyond low-Earth orbit. The system-level redundancy of the U.S. and Russian segments, which can maintain critical functions in the event of failures, make the station an ideal testbed for this upgraded system.

The initial ECLSS was an open-loop, non-regenerative system. The Exploration ECLSS is a regenerative air and water system. Ongoing upgrades will continue to improve reclamation of water and air and overall system reliability.

The Water Recovery System provides clean water for astronaut use by recycling urine; cabin humidity condensate from crew sweat, respiration, and hygiene; and water recovered from the Air Revitalization System. The Urine Processor Assembly, part of the Water Recovery

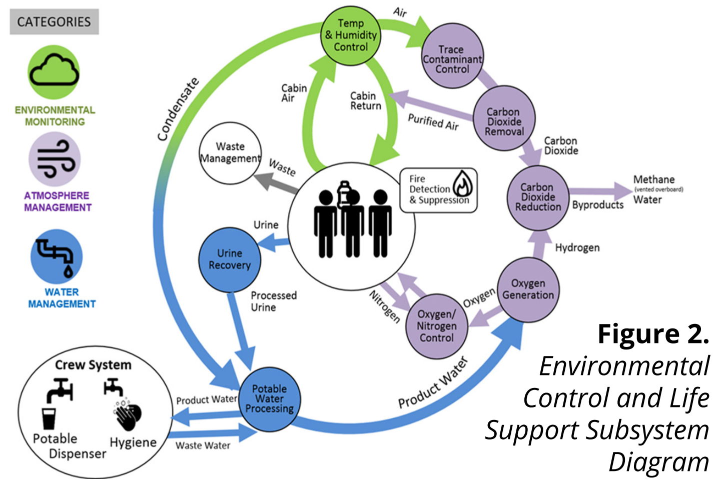


Figure 2. *Environmental Control and Life Support Subsystem Diagram*

System, was designed for 85 percent water recovery from crew urine. Over the last year, that performance has improved to 87 percent thanks to analysis that showed there was still a margin against calcium sulfate precipitation.

The combined water recycling system on the International Space Station has now reached a theoretical 98 percent, Mars-class efficiency thanks to another new device being tested on board — the Brine Processor Assembly, which demonstrates the ability to recover additional water from crew urine and reduce water waste. Special membranes in the system retain contaminates and pass water vapor into the cabin's atmosphere, where it is captured and delivered to a water processing system.

The Air Revitalization System has also evolved, with additional upgrades planned to launch in the near term. A new generation Carbon Dioxide Removal Assembly, known as the 4-bed CO2 scrubber, has demonstrated improved performance and reliability over its predecessor. This improved performance has enabled lower carbon dioxide levels, improving crew health, and has reduced crew time for maintenance.

The original Oxygen Generation Assembly is also being upgraded into the Advanced Oxygen Generation Assembly, which will fly to the space station in FY25. This new system will feature a more robust cell stack design that reduces mass and maintenance of replacement parts, which NASA estimates will save hundreds of pounds in spares for future long-duration missions.

A redesigned Sabatier carbon dioxide reduction system, which produces methane from CO2 and hydrogen, will also fly to the station in FY25. This will be a redesigned reflight of a previous Sabatier system that failed because of catalyst bed contamination and degradation.

When integrated together, the Exploration ECLSS air systems will recover approximately 50 percent of the oxygen from carbon dioxide. In addition, NASA has been working on advanced carbon dioxide reduction technologies that will potentially recover more than 75 percent of oxygen from carbon dioxide. Those technology demonstrations are planned for late in the decade, either on the space station or follow-on commercial low-Earth orbit destinations.

Equally important — if not more important than ECLSS loop closure — is ECLSS system reliability. One of the major lessons learned from ECLSS on the space station is that no matter how much systems are ground tested, new issues are discovered when they are integrated in the space environment. Even after operating regenerative ECLSS for over 14 years, NASA is still learning.

While the proximity of low-Earth orbit enables relatively easy launch of replacement components, long-duration missions beyond low-Earth orbit must have either a highly reliable ECLSS or the ability to launch with thousands of pounds of spare parts. The ECLSS evolution and testing that has occurred and is still planned on the space station has already improved system reliability, measured in spares mass required for a Mars mission, by more than 35 percent. Additional testing on the orbiting laboratory, coupled with ground testing, will continue to improve our understanding of these systems and their reliability.

Navigation

The Orion spacecraft uses an optical navigation system called OpNav to voyage to and from the Moon. OpNav uses images of the Moon and Earth, looking at their sizes and positions to determine Orion's angle and distance from these bodies, to keep Orion on course. The system also can help Orion autonomously return home if the spacecraft loses communication with Earth.

The International Space Station is demonstrating the effectiveness of this approach by testing OpNav. The station investigation uses two cameras mounted on a plate and offset by about 20 degrees. The plate is installed in the station's cupola, a seven-windowed observation module, with the cameras pointing out one of the windows. One camera captures images of stars and the other takes photos of specified views of the Moon. OpNav software then analyzes these images and determine the station's position in space. Since the station's position is always known, and the time at which a particular photo was taken is also known, NASA engineers can compare the OpNav algorithm results with the actual location to judge the system's accuracy.

The Sextant Navigation for Exploration Missions focuses on stability and star sighting opportunities in microgravity. Astronauts have demonstrated that the handheld sextant intended for use on future Orion exploration missions can successfully be used as a backup navigation capability in a microgravity environment.

Another, more modern sextant technology on the space station is also contributing to future navigation capabilities. The external Neutron-star Interior Composition Explorer (NICER) external payload studies the composition of neutron stars and pulsars deep in the universe, adding to humanity's understanding of astrophysics. The Station Explorer for X-ray Timing and Navigation Technology (SEXTANT), a NICER experiment, detected pulsars' repeated, consistent flashes of radiation to demonstrate X-ray navigation for the first time in space. X-ray navigation uses the specific timing of pulsars to determine position, just as a GPS reciever on Earth uses the timing supplied by GPS satellites. When developed to an operational capability, X-ray navigation could allow precision navigation anywhere in the solar system.

Food Storage Systems

The eXposed Root On-Orbit Test System (XROOTS) experiment uses aeroponic and hydroponic systems to grow fresh food without space-consuming growth media. XROOTS grows plants in the microgravity environment and evaluates nutrient delivery and recovery techniques over the course of a full plant growth cycle, from germination to maturity. The system uses multiple independent growth chambers in parallel to evaluate alternative methods and configurations; the results could lead to large-scale food production systems. This would offer reductions in the weight requirements for such systems and fresh food produced in situ, allowing more room for other valuable cargo.

Figure 3. *Astronaut Frank Rubio checks tomato plants growing inside the International Space Station for the XROOTS space botany study.*

Extravehicular Activities

Extravehicular activities, or spacewalks, have been critical to the assembly and maintenance of the International Space Station. Similarly, spacewalks will be essential to establishing and expanding our presence in cislunar space and on the lunar surface. To date, NASA astronauts aboard the station have performed more than 85 spacewalks, contributing to our understanding of working outside in the vacuum of space.

As we look forward to cislunar and lunar exploration, the station is also playing an important role in demonstrating technologies that will enable astronauts to work outside the Gateway lunar space station and on the lunar surface. These efforts include testing active thermal control components and demonstrating the functionality of next-generation spacesuits, as well as determining whether crew members can complete certain suit maintenance tasks in microgravity that would otherwise require returning parts of the suit to the ground for evaluation and testing.

Human Research

Crew health and performance are critical to successful human exploration beyond low-Earth orbit. NASA's Human Research Program investigates and mitigates the biggest risks to human health and performance, providing essential countermeasures and technologies for human space exploration using the International Space Station's unique capabilities. Those risks include physiological effects from radiation, microgravity, and planetary environments, as well as unique challenges in medical treatment, human factors, and behavioral health support. The Human Research Program is responsible for understanding and mitigating these risks to astronaut health and performance to ensure crew members remain healthy and productive during long-term missions beyond low-Earth orbit.

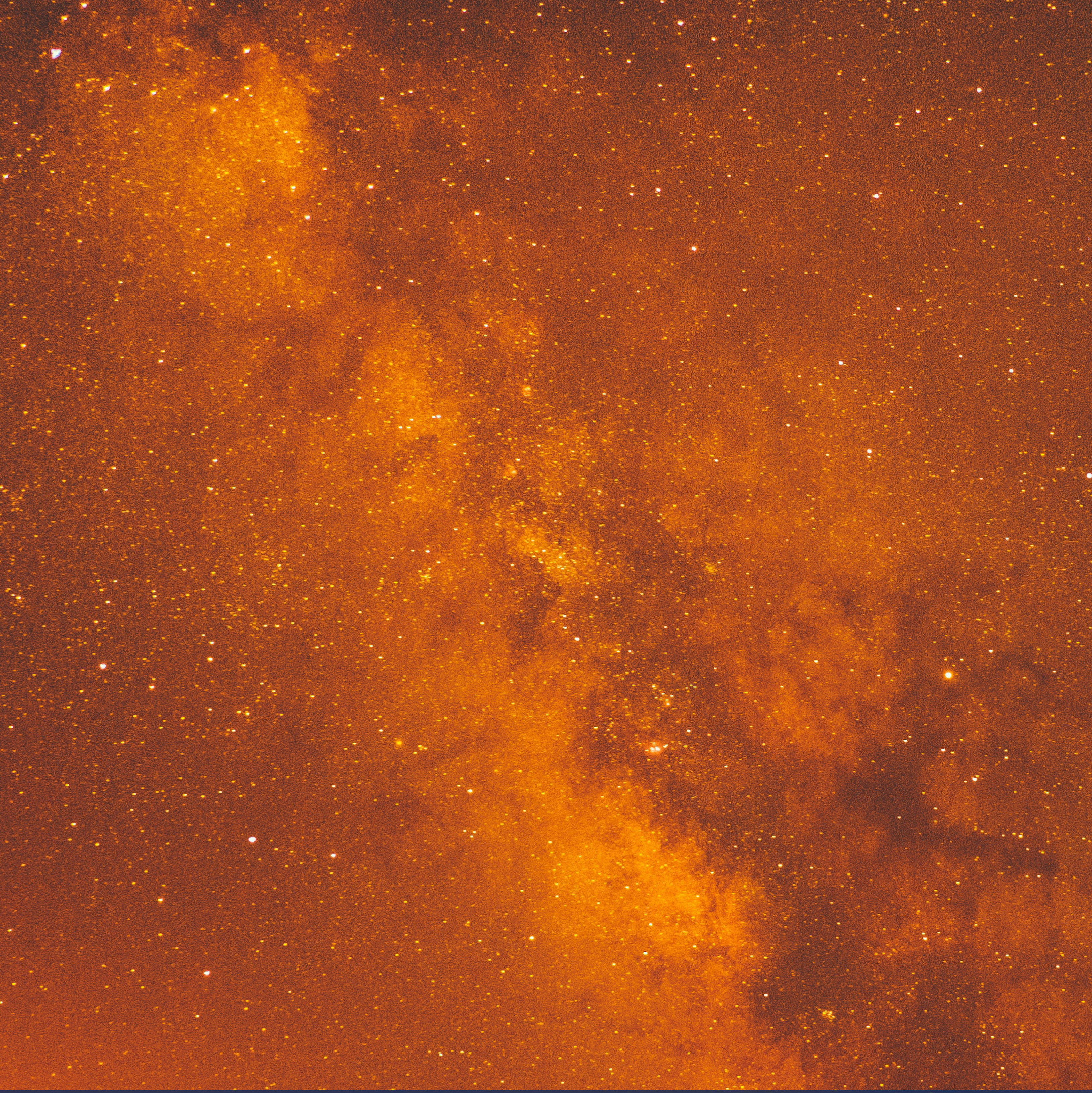
Key Take-Aways

For more than 20 years, scientists have used the International Space Station to conduct research into biological, physical, biomedicine, materials, and Earth and space science.

The International Space Station offers a unique platform for demonstrating new technology in space, including the technologies needed for the Artemis missions to the Moon and future missions to Mars.

Crew members aboard the International Space Stations have been a critical part of the experiments, volunteering as test subjects for research into human adaptation to microgravity.

Exploration-focused research and development on the space station includes navigation, environmental control and life support systems, food storage systems, extravehicular activities, spacesuits, and human research.



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