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## NASA’s Approach to Lunar Communication and Navigation: Artemis and Beyond

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### Abstract

NASA’s Space Communications and Navigation (SCaN) program is developing a support structure of networks, partners, and technologies to provide communication, position, navigation, and timing services at the Moon. In this paper, we describe the progress and status of these diverse efforts and the ways in which they will be used during NASA’s crewed lunar exploration program, Artemis. We provide an update on developments at NASA targeting cislunar space, including the Orion Artemis II Optical Communications System (O2O) demonstration mission, Lunar Exploration Ground Sites (LEGS) that will offer a dedicated Direct to Earth (DTE) capability servicing the cislunar region, and a recently released RFP for commercial lunar communications relay and navigation services and Direct to Earth (DTE) communications capabilities. We also describe the status and role of the LunaNet Interoperability Specification (LNIS), a collaborative standards framework developed by NASA, international partner agencies, and commercial stakeholders. A common thread, weaving these efforts together, is the support of commercial enterprises that can meet the Artemis challenge. Together, these projects and activities will enable safe, robust, and reliable communications and position, navigation, and timing (PNT) services for both crewed and uncrewed missions across cislunar space. SCaN and its partners are helping to build the foundation for a long term, sustainable human presence at the Moon – one that will set the stage for similar efforts at Mars.

**Keywords:** Lunar, Communications, Position Navigation and Timing, Commercial, Partnerships

### Acronyms/Abbreviations

Acronym	Definition
BWG	Beam Waveguide
CISRO	Commonwealth Scientific and Industrial Research Organization
CPNT	Communications, Position, Navigation and Timing
DLEU	DSN Lunar Exploration Upgrades
DSN	Deep Space Network
DTE	Direct to Earth
DSS	Deep Space Station
EHP	Extravehicular Activity (EVA) and Human Surface Mobility (HSM) program
ESA	European Space Agency
EVA	Extravehicular Activity
GEO	Geosynchronous Orbit
HLS	Human Landing System
HSM	Human Space Mobility
ICSIS	International Communication Systems Interoperability Standard
IM	Intuitive Machines
JAXA	Japan Aerospace Exploration Agency
LCOT	Low-Cost Optical Terminal

LCRNS	Lunar Communications Relay and Navigation Services
LEGS	Lunar Exploration Ground Sites
LEO	Low Earth Orbit
LNIS	LunaNet Interoperability Specification
M2M	Moon to Mars
MAPP	Mobile Autonomous Prospecting Platform
NASA	National Aeronautics and Space Administration
NRHO	Near-Rectilinear Halo Orbit
NSN	Near Space Network
O2O	Orion Artemis II Optical Communications
PNT	Position, Navigation, and Timing
PPP	Private-Public Partnership
RF	Radio Frequency
SANSA	South African National Space Agency
SBIR	Small Business Innovative Research
SCaN	Space Communications and Navigation
UHF	Ultra High Frequency
3GPP	3 <sup>rd</sup> Generation Partnership Project

## 1. Introduction: NASA's Lunar Vision and the Space Communications and Navigation Program

NASA has embarked on a new journey to the Moon that will create a sustainable human lunar presence as a critical step to later human exploration of Mars. This journey began with the launch of Artemis I in November 2022. The Agency's exploration vision is founded on pillars of science, national posture, and inspiration. This foundation is the basis of the Moon to Mars (M2M) objectives [1] which span goal areas ranging from lunar and planetary science to transportation and habitation, as well as lunar and Mars infrastructure. In all, there are 63

SCaN's current architecture is comprised of Near Space Network (NSN) assets spanning ground networks and space-relay elements in geostationary orbit, and the Deep Space Network (DSN) with large aperture antennas at three global sites designed to support missions operating in deep space (nominally beyond 2-million kilometers from Earth). The CPNT architecture challenges presented by the M2M vision are not trivial. SCaN's approach relies on developing partnerships with commercial industry to meet the demands of the mission. This paper explores some of the architectural elements being pursued to achieve the M2M vision, and how,



Fig. 1. Moon To Mars Architectural Segments Progressively Increase in Complexity and Objective Satisfaction

M2M objectives, and 9 recurring tenets, or common themes, that apply to all objectives. These tenets include industry collaboration, interoperability, and commerce and space development. The Space Communications and Navigation Program (SCaN) at NASA is helping develop, integrate, and manage the collective communications, position, navigation, and timing (CPNT) infrastructure that will enable this bold vision.

The exploration roadmap is comprised of segments (Figure 1), beginning with human lunar return, expanding operations to support complex orbital and surface missions during the foundational exploration segment, and eventually progressing to sustained lunar evolution, with active human presence on and around the Moon, regional and global utilization, and robust economic activity. Mature operations and capabilities at the Moon then form the basis for humans returning to Mars.

building on lessons from near-Earth commercialization and market advancements, commercial partners, capabilities, and services are being integrated.

## 2. Architectural Approach

The Human Lunar Return segment of NASA's M2M program represents the Agency and its partners' first critical steps in establishing a sustainable and long-term human presence at the Moon. Its centerpiece, the Artemis II through Artemis V missions, will achieve a series of major milestones: Artemis II will return crewed spacecraft to cislunar space, Artemis III and V will land human beings on the lunar surface for the first time since 1972, and Artemis IV will perform the initial assembly of the Lunar Gateway space station in a near-rectilinear halo orbit (NRHO) orbit around the Moon [2].

NASA sees these as steppingstones towards a future ecosystem with crewed lunar rovers, cargo deliveries,

and an array of supporting vehicles across the Moon's surface and in various lunar orbits. Some of these are expected to be government operated missions; others commercial, such the landers and orbiting spacecraft the Agency is supported through the Commercial Lunar Payload Services program. NASA is driven by the dynamic vision for cislunar space articulated in the National Cislunar Science and Technology Strategy released by the White House in November of 2022 [3]. However, this creates new challenges for how to best provide CPNT support for a rising number of users whose individual data needs are also expected to increase. Furthermore, this increase in users also creates new safety of navigation risks for which robust CPNT infrastructure is the only clear mitigation.

These discussions have gained urgency as experience has shown that supporting even a single crewed vehicle in cislunar space in the model of Artemis I and II pushes SCaN's present-day network assets to their limit. Requirements such as having a Deep Space Network (DSN) "hot-spare" for human spaceflight rated vehicles places a substantial load on the network. Asset contention caused by high demand during the uncrewed Artemis I mission led to major impacts on even flagship robotic missions like the James Webb Space Telescope [4]. While steps have been taken to mitigate the impact for Artemis II, it is still anticipated to be tremendously disruptive to the science mission community.

Future Artemis missions in the human lunar return segment will have even higher demand. Artemis III will see two crewed vehicles, the Orion capsule, and the SpaceX Human Landing System (HLS), operating together in cislunar space, both with DSN support. The Gateway Space Station deployed by Artemis IV is designed to receive ongoing 24/7 support from Earth for monitoring and scientific experiments whether astronauts are on board or not. The requirements will continue to intensify, driven by increasingly complex missions, parallel efforts by partners, and the physical constraints of surface operations at the lunar south pole, where intermittent Earth visibility and rugged topography complicate direct-to-Earth communications.

SCaN is actively charting a course to meet these user needs. Infrastructure upgrades, new capabilities, and new technologies are being funded, developed, and built by the program to ensure all users in this vibrant cislunar ecosystem can be confident in their CPNT support. Across these cases, SCaN's efforts are supported by a strategy to establish partnerships with industry and build commercial partners. This approach aligns with long standing Office of Management and Budget tenets, as well as the National Space Policy released in 2020 [5], that encourage NASA to draw upon commercial services wherever possible. It also seeks to build on the Agency's ongoing success drawing excellence from the commercial space marketplace into USG operations.

SCaN continues to be a key part of this story in Low Earth Orbit (LEO); the program is excited to engage in cislunar space to unlock the next generation of commercial communications services.

### *2.1 Artemis II Optical Communications System*

The 10-day Artemis II flight is the next in the series of Artemis missions and the first with crew. The flight path will send the four astronauts around the backside of the Moon, approximately 4600 miles beyond the lunar far side's surface, before returning home. The focus of the mission will be to prove out critical life support systems and practice operations essential to the success of subsequent flights.

From a communications and tracking perspective, Artemis II will be supported by SCaN's existing network assets. While in Earth orbit, the Orion crew vehicle will receive support from the Tracking and Data Relay satellites of the NSN. When Orion travels out to and around the Moon, SCaN's Deep Space Network will provide services.

Fundamentally, radio frequency (RF) communications will be limiting for sustained lunar operations that will require both higher data rates and volumes as complexity of operations grows. Thus, on Artemis II, NASA is taking the opportunity to demonstrate a free-space optical communications terminal capable of both transmitting and receiving high-rate laser communication signals. This portion of Artemis II is the Orion Artemis II Optical Communications demonstration, or "O2O."

O2O will nominally provide an 80 Mbps (with capability up to 260 Mbps) downlink and a 20 Mbps uplink. Given that Orion subsystems are expected to generate ~ 300 GB of data on orbit during the 10-day mission, a one-hour downlink per day using O2O represents a 6-fold increase in data transmission over using S-band RF communications. [6]

The O2O system consists of four major system elements: the Orion spacecraft element, the space terminal element, the ground segment, and the Orion operations element. For this discussion, the ground terminal subcomponent of the ground segment is a key focal point. These are the physical optical terminals residing at the primary ground station at the White Sands Complex in New Mexico, and the backup terminal at the Table Mountain Facility in California. NASA is collaborating with the Australia National University to potentially provide third terminal / ground site capability. In parallel with the primary and backup ground terminals, NASA has invested in the development of a low-cost of production, self-contained, and mostly commercial off-the-shelf system referred to as LCOT, the low-cost optical terminal (Figure 2).



Fig. 2. The Low-Cost Optical Terminal at NASA's Goddard Space Flight Center in Greenbelt, Maryland.

The O2O demonstration and LCOT development are steppingstones toward a future state of diverse optical ground terminal sites and services that can be delivered by commercial industry to enable resilient and robust high-rate communications from the Moon and beyond. Establishing a strong domestic supply chain is key. To that end, SCaN has supported a small business collaboration for the development of a through a small business collaboration, SCaN funded the successful development of a new piece of laser technology. The Basestation Optical Laser Terminal developed by Fibertek Inc., is a four-channel laser unit that could enable the transmission of high-power communications – such as on O2O. In September 2023, Fibertek's technology was integrated into NASA's low-cost terminal ground station and successfully tested, exemplifying the commercial partnership model SCaN is pursuing to support the early Artemis missions. [7]

## 2.2 Growing Earth-based Capacity

SCaN is working actively to enhance its ability to send and receive signals to cislunar space from Earth-based tracking stations. This has historically been a key role for the DSN and its 16 large aperture antennas placed at sites in the US (Goldstone), Spain (Madrid) and Australia (Canberra). This allocation of work is planned to continue through the Lunar Return Segment, even as that demand may be reduced through the introduction of lunar relay infrastructure.

DSN Lunar Exploration Upgrades (DLEU) project encompasses a critical set of upgrades being executed on six DSN antennas, two at each DSN site. To address lunar science and Artemis user needs, it seeks to increase data rates by adding near-Earth K-band uplink, enabling concurrent operations across multiple bands (including simultaneous uplinks and downlinks), and increasing data rates across a range of bands. Upgrades have already been completed for three antennas, and five of six are on track to be completed in time for Artemis III.

The DSN Aperture Enhancement Project (DAEP) is focused on both select upgrades and building entirely new 34-meter Beam Waveguide (BWG) apertures. These will serve both users in cislunar space, and robotic science missions in deep space. At Canberra, two antennas, the Deep Space Station 35 (DSS-35) and DSS-36 are already completed, with a third antenna, DSS-33 planned for delivery in 2029. At Madrid, two new antennas, DSS-56, and DSS-53, which became operational in January 2021, and February 2022, respectively. At Goldstone in California, one new antenna (DSS-23) is in-progress with a planned delivery date in April 2026. Any further expansion will be based on the DSN Futures Study currently underway, agency requirements, and available support.

In parallel with upgrades to the DSN, SCaN is invested in a new capability for its NSN: Lunar Exploration Ground Sites (LEGS). The LEGS project was established to provide at least 18-m class performance to augment DTE capacity for missions from GEO out to 2 million km. It is designed to alleviate pressure on DSN 34-m assets, and to eventually become the leading NASA network providing DTE support to users in cislunar space.

The Agency is initiating work through the development of three initial LEGS sites with 18-m antennas that will serve as government-owned-contractor-operated assets, placed around the globe to provide universal coverage (Figure 3). Site 1 will be located at NASA's White Sands Complex, with Sites 2 and 3 being pursued in partnership with the South African National Space Agency (SANSA) in South Africa and the Australian Space Agency and Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia. NASA's goal is to establish the first three LEGS stations ahead of the Gateway launch, as the envisioned primary function of these initial assets will be to fulfil the space station's 24x7 coverage requirement.

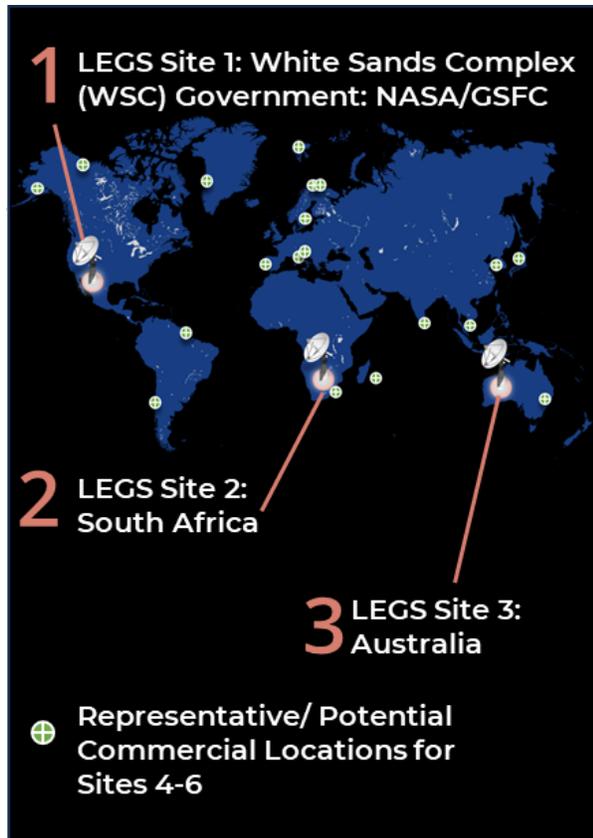


Fig. 3. Lunar Exploration Ground Segment blends government and commercial capabilities

LEGS, unlike DSN, has been designed from the ground up to seed a commercial services marketplace. NASA will define service requirements and an architecture for cislunar DTE communications and send a demand signal to industry by committing to the three initial antennas on its own. In parallel, NASA initiated an NSN Services procurement process in Q1 2023 seeking additional ground stations (Sites 4-6), with the ultimate services to be determined based on its outcome. Offerings are anticipated to include capabilities for S, X, and Ka-band transmit-and-receive services.

Even before that RFP is awarded, however, signs of success in the Agency's commercial vision for LEGS vision have emerged. Commercial providers are already preparing to offer services that are interoperable with the LEGS service architecture. KSAT has announced a "20 Meter Class" network which directly cites LEGS compatibility and will even use the same antenna manufacturer as LEGS [8]. Mirroring its success in spurring a commercial services economy for DTE services in LEO, NASA is spurring investment in the cislunar DTE ecosystem, while ensuring that the infrastructure will be suitable for NASA mission requirements.

### 2.3 Surface Connectivity

As the complexity of lunar operations increases, direct communications between astronauts, surface elements, and science payloads will become increasingly important to enable the desired level of autonomy associated with sustained human presence. Legacy solutions, such as ultra-high-frequency (UHF) communications do not provide the requisite operating ranges, such as 2km walking distance from the lander and vehicle traverses of up to 10km.

NASA is tapping into commercial industry capability and standards such as the 3<sup>rd</sup> Generation Partnership Project (3GPP) to bring a more scalable and capable solution to bear. In 2020, a tipping point demonstration was awarded to Nokia to demonstrate 4G/LTE communications on the lunar surface. The Nokia "network in box" will connect the Intuitive Machines' Nova-C lunar lander with Lunar Outpost's Mobile Autonomous Prospecting Platform (MAPP) rover and Intuitive Machines' (IM) Micro-Nova hopper, testing its viability over both near and far distances (Figure 4) [9]. The mission is slated for an early 2025 launch.

After the IM-2 mission, NASA is slated to execute a communication demonstration on Artemis III (A-III) to demonstrate 3GPP surface communications. The objective of this demonstration is to evaluate a long-range lunar surface communications capability, informing architecture decisions for future missions. NASA awarded Axiom Space a contract to adapt the lunar spacesuit design to incorporate 4G/LTE capability as part of the AIII mission. Nokia and Axiom Space are collaborating to enable HD video, telemetry data and voice transmission over multiple km [10]. SCan is also developing a reference design to meet lunar CPNT requirements through the Artemis V and beyond timeframe.

Investments in commercial capability here on Earth will also benefit lunar surface communications. For example, Small Business Innovative Research (SBIR) grant dollars awarded to CesiumAstro for development of phased array antenna technology have provided a path forward for lunar phased array terminals that can meet the NASA Extravehicular Activity (EVA) and Human Surface Mobility (HSM) (Extravehicular Activity and Human Surface Mobility (EHP) program's requirements for lunar terrain vehicle mobile communications [11].



Fig. 4. Artist rendering of the Lunar Outpost Mobile Autonomous Prospecting Platform (MAPP) rover with Nokia antennas extended. Image credit: Nokia/Intuitive Machines.

## 2.4 Cislunar Relay

Future cislunar missions and spacecraft will need relay services to maintain communication with Earth as well as connectivity and space situational awareness. Unlike DTE services at the Moon, lunar relay can provide complete coverage of both the surface and a service volume above it, including on the far side. This includes GPS-like navigational support for surface and orbital users. Furthermore, an effective and robust relay network can reduce the load on Earth-side DTE infrastructure by handling communications within cislunar space locally and consolidating backhaul needs to a single aperture.

NASA's vision for a robust cislunar relay network will ensure CPNT support at the Moon's South Pole, the primary target of Lunar Return Segment Artemis missions and future scientific missions. During the initial operational capability phase, orbital lunar assets will provide intermittent communications relay to Earth and in-situ PNT to a limited South Pole service volume. As M2M program missions grow in size, duration, and complexity, this relay system will expand to cover the Moon's far side and eventually achieve global coverage (Figure 5).

The Agency plans to establish Lunar Communication Relay and Navigation Systems (LCRNS) through the procurement of commercial services. The NSN Request for Proposals released in Q1 2023 defined a stepped series of service requirements such as service volumes and coverages to meet. These services are intended to be fully end-to-end, where providers will be responsible for data return to Earth and delivery to NASA without creating any further burdens on NASA's DTE systems such as DSN and LEGS.

The Agency's execution of this commercial strategy in a "green field" provides an opportunity to take a standards-first approach to cislunar relay. Unlike commercial LEO, where vendor lock concerns remain a key challenge, interoperability will be built into cislunar commercial service infrastructure from day one. NASA

is making technology investments to ensure this is the case, including recent awards to CesiumAstro to develop cislunar PNT RF transceivers to Agency specifications [12].

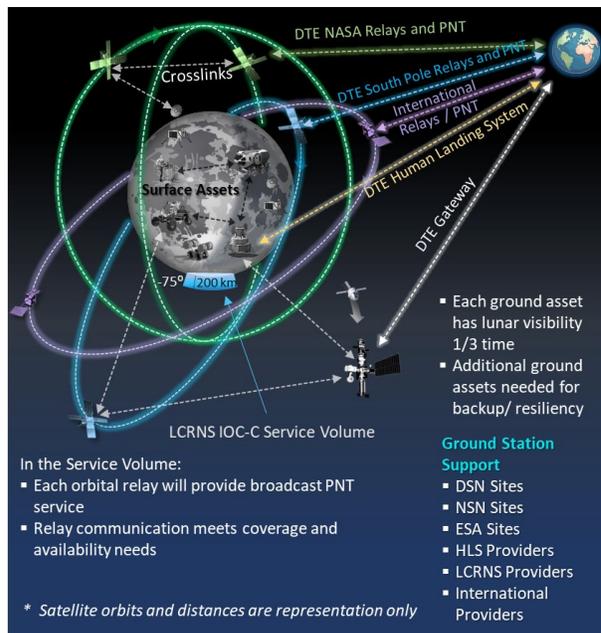


Fig. 5. C&PNT Assets Serving the Moon Region

Lunar relay service infrastructure is intended to support all NASA Artemis mission users as well as international partner missions. Therefore, these and all other lunar relay services will be compliant with the LunaNet Interoperability Specification (LNIS). International space agencies also intend to provide compatible lunar relay and orbital CPNT assets, including the Japan Aerospace Exploration Agency (JAXA) and the European Space Agency (ESA). ESA's Moonlight program is following SCA's commercial approach, with a Private-Public Partnership (PPP) which will similarly spur commercial investment and ensure cross compatibility [13].

The clear demand signal being created by NASA and its partners, alongside the burgeoning commercial space enterprise in cislunar space, is already impacting industry decisions. Intuitive Machines has announced an effort to deploy a constellation of lunar communication relays providing lunar relay as a service [14].

## 2.5 Interoperability as a Cornerstone

Collaboration in the envisioned ecosystem of various networks and mission users as the cislunar civil and commercial market develops will rely on interoperability. In the context of the overall M2M architecture, interoperability and collaboration with both industry and international partners have been identified as recurring tenets [1] representing strategic priorities for

the entire lunar effort. Ultimately, interoperability will depend on the extent that service providers follow mutually developed and agreed-upon standards for the services and interfaces allowing networks to provide seamless services to multiple users. During the initial crewed Artemis missions, a variety of interface standards will enable interoperability. These include the LNIS [15], the International Communication Systems Interoperability Standard (ICSIS), terrestrial wireless cellular standards, and other similar coordination with industry and international partners.

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 standards, protocols, and interface requirements that enable interoperability and are defined within the LNIS document. The LNIS is fundamental to the establishment of a cooperative lunar network involving space agency partners, their associated commercial vendors, and their mission users. NASA is anticipating that other government or commercial entities involved with communication and navigation services as mission users or service providers will voluntarily comply with the LNIS standards and protocols in the interest of maximizing their own possibilities for compatibility with other users and service providers.

NASA, ESA, and JAXA are working jointly to develop and update the LNIS document. As the set of public and private sector providers grows with the lunar market, LNIS will continue to be shared with the community at large to allow all contributors to comment and shape the evolution of LunaNet.

### 3. Conclusions

Artemis and associated missions to cislunar space by NASA and its partners are primed to dramatically increase demand for CPNT services at the Moon. This surge in users in cislunar space will challenge existing infrastructure, necessitating significant network upgrades and new technologies. Additionally, the increased activity will heighten safety of navigation risks and create new demand for robust PNT systems. SCaN is rising to meet this challenge, with a strategy that cuts across its equities with a clear and unwavering vision: that the future of cislunar services will emerge from an effort to build commercial partners.

To facilitate the growth and development of a healthy cislunar market, NASA is working across several axes. CLPS and Artemis themselves serve as potential anchor tenants to generate initial demand for emergent commercial services—but as occurred with the Agency’s success seeding LEO DTE, the role of NASA in business cases is expected to diminish through time.

In parallel, NASA SCaN is making a series of investments in technologies, capabilities, and demonstration missions. Across these efforts, the program is taking a standards-first approach. This is encapsulated most directly in its efforts with LNIS. However, the role of standards is key in context dependent efforts to spur commercial development that is interwoven across all its initiatives, including O2O, LEGS, LCRNS and 3GPP surface comms. Across these cases, the program is working to seed commercial infrastructure that lunar missions can rely on for reliable, innovative, and cost-effective CPNT services.

Exploration and science at the Moon is emerging as a global strategic priority. The United States, through both the Artemis program and its role as a founding signatory in the 43-and-counting member Artemis Accords, seeks to establish a leadership role in cislunar space. The Cislunar CPNT strategy being pursued by NASA SCaN and its partners is a key part of this story. It relies on a steadfast belief that, as the Agency has accomplished in LEO, putting commercial and government entities into partnership can drive development and unlock the innovation economy at the heart of our nations. Space is hard, and the Moon is harder. Through a strategy that centers on collaboration and partnerships, we can make the impossible possible and create a true foundation for the Artemis generation—and our next steps, towards Mars.

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