

NASA's Space Launch System: A Transformative Capability for Exploration

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ABSTRACT

Currently making rapid progress toward first launch in 2018, NASA's exploration-class Space Launch System (SLS) represents a game-changing new spaceflight capability, enabling mission profiles that are currently impossible. Designed to launch human deep-space missions farther into space than ever before, the initial configuration of SLS will be able to deliver more than 70 metric tons of payload to low Earth orbit (LEO), and will send NASA's new Orion crew vehicle into lunar orbit. Plans call for the rocket to evolve on its second flight, via a new upper stage, to a more powerful configuration capable of lofting 105 t to LEO or comanifesting additional systems with Orion on launches to the lunar vicinity. Ultimately, SLS will evolve to a configuration capable of delivering more than 130 t to LEO. SLS is a foundational asset for NASA's Journey to Mars, and has been recognized by the International Space Exploration Coordination Group as a key element for cooperative missions beyond LEO. In order to enable human deep-space exploration, SLS provides unrivaled mass, volume, and departure energy for payloads, offering numerous benefits for a variety of other missions. For robotic science probes to the outer solar system, for example, SLS can cut transit times to less than half that of currently available vehicles, producing earlier data return, enhancing iterative exploration, and reducing mission cost and risk. In the field of astrophysics, SLS' high payload volume, in the form of payload fairings with a diameter of up to 10 meters, creates the opportunity for launch of large-aperture telescopes providing an unprecedented look at our universe, and offers the ability to conduct crewed servicing missions to observatories stationed at locations beyond low Earth orbit. At the other end of the spectrum, SLS opens access to deep space for low-cost missions in the form of smallsats. The first launch of SLS will deliver beyond LEO 13 6U smallsat payloads, representing multiple disciplines, including three spacecraft competitively chosen through NASA's Centennial Challenges competition. Private organizations have also identified benefits of SLS for unique public-private partnerships. This paper will give an overview of SLS' capabilities and its current status, and discuss the vehicle's potential for human exploration of deep space and other game-changing utilization opportunities.

KEYWORDS: [Space Launch System, SLS, Launch Vehicles, Human Space Exploration, Capabilities]

INTRODUCTION

Conceived and designed to enable human exploration of deep space, NASA's Space Launch System represents a transformative capability for a wide range of potential missions. The super-heavy-lift launch vehicle's primary purpose will be to enable the agency's Journey to Mars, propelling humans beyond low Earth orbit for the first time in almost

half a century, and then supporting previously-impossible missions farther into space than ever before, demonstrating the capabilities that will be necessary for crewed landings on the Red Planet. In providing the requirement performance for that task, SLS provides capabilities that are paradigm-shifting for spacecraft designers and mission planners, enabling architectures and mission profiles that have never before been possible.

SLS is designed to evolve to deliver greater performance and to be configurable to support different types of missions, providing an affordable and sustainable path forward that delivers new vehicle capabilities as mission requirements demand them. The initial configuration of SLS, known as Block 1, was designed to support an initial demonstration flight as expeditiously as possible, and is making progress toward launch in two years. (Fig. 1) This configuration, which could deliver greater than 70 metric tons to low Earth orbit, will be able to launch NASA's Orion crew vehicle into lunar orbit.



Figure 1. Artist's rendition of Space Launch System on its mobile launcher.

For its second flight, to fly no earlier than 2021, SLS will evolve into a more-capable configuration, the Block 1B vehicle, which will increase the vehicle's payload-to-LEO capability to 105 metric tons. The third configuration, Block 2, will be able to deliver 130 metric tons to LEO. The Block 1B and Block 2 vehicles can be configured to carry either the Orion crew vehicle with an additional payload, or to carry a large primary payload in a fairing as large as 10 meters in diameter.

NASA is developing SLS in parallel with two other exploration systems development efforts – the Orion

crew vehicle program, managed at NASA's Johnson Space Center, and the Ground Systems Development and Operations program, which is converting the facilities at NASA's Kennedy Space Center in Florida into a next-generation spaceport capable of supporting launches by multiple types of vehicles.

These capabilities are part of a larger NASA strategy of working with commercial partners that will support crew and cargo launches to the International Space Station, while the agency focuses its development efforts on an incremental approach to developing the systems necessary for human exploration beyond Earth orbit and eventually to Mars.

VEHICLE OVERVIEW AND STATUS

The architecture of the SLS initial Block 1 configuration reflects NASA's desire to meet the mandates for heavy-lift capability in the U.S. congressional NASA Authorization Act of 2010 in a manner that is safe, affordable, and sustainable. After input was received from industry and numerous concepts were reviewed, the chosen design was found to enable the safest, most-capable transportation system in the shortest amount of time for the anticipated near-term and long-range budgets.

The SLS operational scheme takes advantage of resources established for the Space Shuttle Program, including workforce, tooling, manufacturing processes, supply chains, transportation logistics, launch infrastructure, and liquid oxygen and hydrogen (LOX/LH₂) propellants and allows the initial configuration of the vehicle to be delivered with only one clean-sheet new development, the Core Stage. In October 2015, the SLS Program completed its Critical Design Review (CDR), the first time a NASA human-class launch vehicle has reached that milestone since the Shuttle Program almost 40 years ago and the first for an exploration-class vehicle since the Saturn V.

The SLS Core Stage, which stores the liquid oxygen (LOX) and liquid hydrogen (LH₂) propellant for four Core Stage engines, represents almost two-thirds of the vehicle's 98-meter height, standing 64m tall, and has a diameter of 8.4m, sharing commonality with the space shuttle's external tank in order to enhance compatibility with equipment and facilities at KSC and elsewhere. At Michoud Assembly Facility (MAF), outside New Orleans, Louisiana, the world's largest space vehicle welding tool, the 52m-tall Vertical Assembly Center (VAC), is currently being used by The Boeing Company, Core Stage prime contractor, to weld barrel sections, rings and domes

together to form the test and flight articles of the propellant tanks for the stage. (Fig. 2)



Figure 2. Production of the structural test article of the liquid hydrogen tank for the SLS Core Stage.

The Core Stage will be powered by four RS-25 engines, which previously served as the Space Shuttle Main Engine (SSME), taking advantage of 30 years of U.S. experience with liquid oxygen and liquid hydrogen, as well as an existing U.S. national infrastructure that includes specialized manufacturing and launching facilities. These human-rated engines support the SLS pursuit of safety, with a record of 100 percent mission success for the engines over 135 flights. At the end of the Space Shuttle Program, 16 RS-25 flight engines and two development engines were transferred to the SLS Program and placed in inventory at NASA's Stennis Space Center, providing enough engines for the first four flights of SLS.

Modifications to Stennis Test Stand A-1 to support RS-25 testing were completed in 2014, and testing has been underway since the beginning of 2015 in preparation for flight certification of the SLS configuration of the engine, including a new engine controller unit. (Fig 3) The testing includes propellant pressure and temperature inlet conditions that will both be higher with SLS than with the shuttle, as well as other SLS-specific performance requirements such as 109 percent thrust versus the shuttle's 104.5 percent thrust. Stennis Test Stand B-2 is being refitted for the SLS "green run" – the test firing of the first Core Stage with four RS-25 engines. The test will be the largest liquid-engine test since stage tests of the Saturn V in the 1960s.



Figure 3: RS-25 testing at Stennis Space Center

The majority of the thrust for the first two minutes of flight will come from a pair of solid rocket boosters, also of Space Shuttle Program heritage. The SLS is upgrading the boosters from the four-segment version flown on the shuttle to a more-powerful five-segment version. Each booster measures 54 m long and 3.7 m in diameter and is capable of generating up to 3.6 million pounds of thrust, the most powerful flight boosters in the world. Although largely similar to the SRBs used on the space shuttle, this upgraded five-segment SRB includes improvements such as a larger nozzle throat and an environmentally-benign insulation and liner material (asbestos-free). In June 2016, the SLS configuration of the booster successfully underwent the second of two Qualification Motor tests, and booster hardware is currently being prepared for first flight. (Fig 4)

In-space propulsion for the Block 1 vehicle will be provided by an Interim Cryogenic Propulsion Stage (ICPS). (Fig.5) In order to expedite earlier initial launch of this new U.S. super-heavy-lift launch capability, the decision was made early in the vehicle's development to leverage the proven Delta



Figure 4: Qualification Motor-2 test of the SLS solid rocket boosters.

Cryogenic Second Stage (DCSS) for SLS in-space propulsion, delaying development of a larger upper stage until the vehicle's Core Stage, the largest new development for the Block 1 vehicle, was more mature.

The Block 1 Spacecraft/Payload Elements include not only the ULA-produced DCSS-derived ICPS but also two adapters, connecting the stage to the Core Stage and to the Orion spacecraft. The ICPS is being produced by United Launch Alliance in Decatur, Ala., under contract to Boeing. The structural test article of the ICPS arrived at Marshall for testing in June 2016, and the flight unit is currently being assembled. (Fig 5)



Figure 5: Event at United Launch Alliance in Decatur, AL marking completion of the ICPS test article.

The Launch Vehicle Stage Adapter, which connects the Core Stage with the ICPS, is being produced by Teledyne Brown Engineering of Huntsville, Ala., and is being welded on-site at Marshall Space Flight Center. A structural test article has been completed, and assembly of the EM-1 flight article is underway. The Orion Stage Adapter, which connects the Orion

spacecraft with the ICPS, is being produced by Marshall Space Flight Center. An Orion Stage Adapter produced by the SLS Program flew successfully on the Exploration Flight Test-1 of Orion in December 2014; and the EM-1 flight unit has been welded at Marshall.

EVOLUTION PLANS AND PROGRESS

While the Program's focus is very much on preparation for the first launch in two years, work is already well underway on development for future missions and evolved configurations of the vehicle.

The second flight of SLS, currently scheduled for no earlier than 2021, will use the Block 1B configuration of the vehicle, capable of delivering 105 metric tons of payload to low Earth orbit. (Fig 6) The Block 1B vehicle will replace the single-engine ICPS with a more-powerful dual-use four-engine Exploration Upper Stage, which will provide both ascent and in-space propulsion. The contract for the EUS has been awarded to Boeing and an agreement has been reached with Aerojet Rocketdyne to provide the stage's RL10-C3 engines. A Preliminary Design Review for the stage is scheduled to begin by the end of the year.

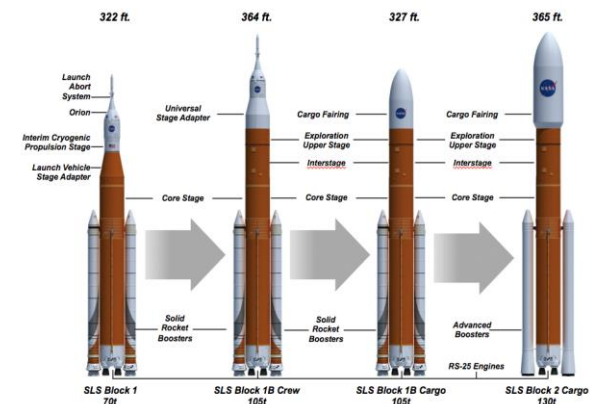


Figure 6: SLS Evolutionary Path

The change from the 5-meter ICPS to the 8.4 meter EUS means that the LVSA and OSA will be supplanted by a Universal Stage Adapter, which will provide room for a comanifested payload to fly on an SLS along with Orion. The Universal Stage Adapter (USA) will be managed by NASA's Glenn Research Center in Cleveland, Ohio. A request for proposals for the adapter was issued in September 2016. Within the USA will be a payload adapter, a demonstrator version of which is currently being built at Marshall Space Flight Center.

Other work for Exploration Mission-2 is also currently taking place. Panels for the second flight core stage have been produced at AMRO in California, and in March 2016, a test-firing of an EM-2 RS-25 engine was performed at Stennis Space Center. Wind tunnel testing is maturing understanding of crew and cargo versions of the Block 1B vehicle.

Work is also currently underway toward making upgrades and affordability enhancements to the RS-25 engines and restarting the production line for the fifth flight of SLS and beyond, after the initial inventory of shuttle RS-25s is expended.

The SLS program has also conducted initial engineering demonstration and risk reduction work on advanced booster technologies and concepts, preparing for a later upgrade from the shuttle-derived boosters to new boosters that will deliver greater performance. With that upgrade, SLS will reach the fully evolved Block 2 configuration.

CAPABILITIES

Space Launch System offers substantial benefits in three primary areas, which offer game-changing opportunities for spacecraft designers and mission planners.

For missions to, or staging in, the Earth-moon vicinity, Space Launch System offers unrivaled mass lift capability. The Block 1B configuration of the vehicle, which will be the version available for payloads during most of the 2020s, will be able to lift 105 metric tons to low Earth orbit, and will be able to deliver 40 metric tons to translunar injection (TLI). The crew configuration of the Block 1B vehicle can carry up to an additional 10 tons of payload along with the Orion spacecraft. The Block 2 configuration will increase that performance to more than 130 metric tons to LEO, and at least 45 t to TLI.

For missions beyond the Earth and moon, SLS offers substantially greater characteristic energy (C3) than any other contemporary launch vehicle. For the missions to the outer planets, for example, this can enable a larger science package, reduced transit times, or both.

Space Launch System also offers greater volume than any other launch vehicle. Beginning with EM-2, the Universal Stage Adapter will allow a payload to fly with Orion with as much accommodation volume as the current industry-high 5-meter fairing. The Block 1B configuration will also enable the use of an 8.4m fairing for primary payloads, and the Block 2 vehicle

will be able to carry 10m fairings with a volume of up to 1,800 cubic meters, several times greater than any currently available fairing.



Figure 8. Fairing options for evolved configurations of Space Launch System.

These primary benefits make possible a variety of secondary benefits. For example, greater payload volume can decrease the need for “origami” deployments, thus decreasing spacecraft complexity and risk. Reducing transit time by enabling a direct trajectory without gravitational assists reduces mission risk and operational cost, and can eliminate the need to design for inner-solar system conditions.

The mass and volume capabilities of SLS also provide unique opportunities for use of smallsats in deep-space. The first launch of SLS, using the Block 1 configuration, will deploy 13 6U CubeSats into deep space. Current planning is looking at increasing that capability to 96U CubeSats for future missions. Depending on the requirements of primary or comanifested payloads, it might also be possible to carry larger ESPA-class payloads as well.

HUMAN SPACEFLIGHT UTILIZATION

The primary purpose of SLS is to enable a new era of human space exploration unlike any before it, with missions that would previously have been impossible. As NASA continues to mature plans for its Journey to Mars, SLS and Orion are foundational assets in that journey. The first human beings to launch on Space Launch System will go farther into space than

anyone ever has, and increasingly ambitious undertakings will follow.

Human exploration for the journey to Mars crosses three thresholds -- Earth Reliant, Proving Ground, and Earth Independent -- each with increasing challenges as humans move farther from Earth. NASA is managing these challenges by developing and demonstrating capabilities in incremental steps. (Fig. 9)



Figure 9. Overview of NASA’s Journey to Mars.

Earth Reliant exploration is focused on research aboard the International Space Station, supported by NASA’s commercial cargo and crew providers. From this world-class microgravity laboratory, the agency is testing technologies and advancing human health and performance research that will enable deep space, long duration missions. NASA will operate the ISS through 2024, encourage commercial development of low-Earth orbit, and develop deep space systems for life support and human health.

In the Proving Ground, NASA will learn to conduct complex operations in a deep space environment that allows crews to return to Earth in a matter of days. Primarily operating in the area of space near the moon, NASA will advance and validate capabilities required for humans to live and work at distances much farther away from our home planet, such as at Mars. This includes a yearlong crewed mission into deep space in the 2020s, verifying habitation and testing our readiness for Mars.

Earth Independent activities build on what is learned on the space station and in deep space to enable human missions to the Mars vicinity. The science missions, already operating independently of Earth today, will pave the way. NASA will send humans to orbit Mars in the early 2030s, study landing and in-

situ resource utilization, and conduct a round-trip robotic sample return mission in the 2020s. Future Mars missions will represent a collaborative effort between NASA and its partners—a global achievement that marks a transition in humanity’s expansion as we go to Mars to seek the potential for sustainable life beyond Earth.

The Journey to Mars is being matured as a capabilities-based framework focused on identifying and developing the systems needed for gaining ever-increasing operational experience in space, growing in duration from a few weeks to years in length, and moving from close proximity to Earth to Mars. The approach is consistent with the Global Exploration Roadmap, a Mars exploration partnership strategy developed by the International Space Exploration Coordination Group (ISECG), consisting of 14 space agencies, including NASA, from nations around the world. The Roadmap, which identifies Mars as “the driving goal of human exploration,” is a living document updated via an ongoing series of meetings between partner agencies and interested stakeholders.

SCIENCE UTILIZATION

While Space Launch System was designed around the goal of enabling human exploration of the solar system, the capabilities of the vehicle to fulfill that charter will also provide game-changing benefits for a range of promising space science missions. The SLS team has participated in technical interchange meetings with members of the science community to further a dialogue on the vehicle’s benefits for future missions and to better define how it could enable them. Taking advantage of the C3, mass and volume capacity that SLS offers will allow spacecraft designers and mission planners to change fundamental assumptions about spacecraft and mission design.

SLS utilization is currently being considered for NASA’s proposed Europa Multiple Flyby Mission, which would provide an unprecedented look at the icy Jovian moon, believed to hold a subsurface ocean with more than twice the quantity of water on Earth, and investigate its potential habitability.

While launch on an Atlas V 551 EELV-baseline vehicle could require a Venus-Earth-Earth gravitational assist trajectory requiring 7 to 8 years, launch on SLS would enable a direct transit to the Jovian system in less than three years, providing far earlier science return and reduced operational costs, among other benefits. (Fig. 10) With consideration currently ongoing of a follow-up Europa lander mission, the earlier science return could allow use of

data from the flyby mission to inform the lander mission, without a substantial delay to the latter.

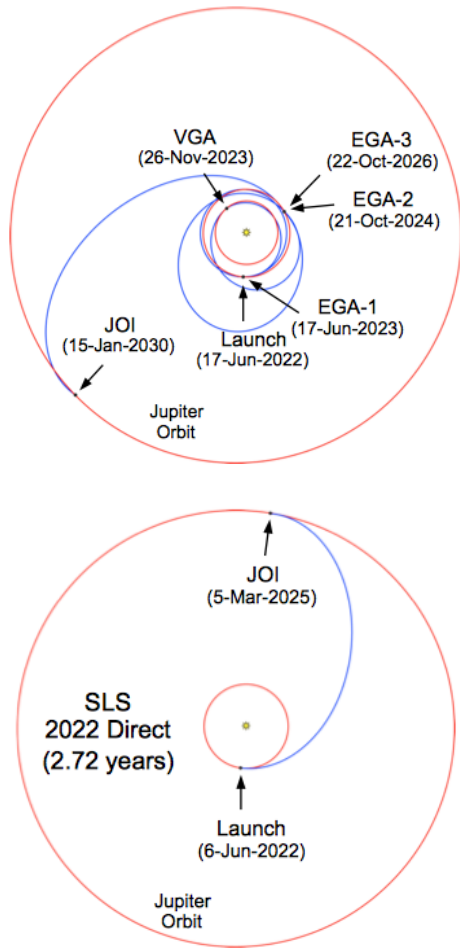


Figure 10. Gravitational-assist trajectory to Europa enabled by current EELVs (top) versus direct trajectory enabled by SLS (bottom).

Europa mission analysis also serves as a test case for how SLS could benefit outer-planet exploration. One of the major benefits to the science community from the Mars Program has been the ability to learn from one mission and use that knowledge when formulating a near-term future investigation. The paradigm for outer planet exploration has necessitated very long cruise times, which, among other things, make it impossible to have a rapid turnaround in penetrating the mysteries that the “ocean world” icy moons of the outer planets possess. The availability of the SLS breaks this model, and allows for significant transit-time reduction.

In the area of payload volume capacity, a large-aperture space telescope offers a good case study. Concept evaluation has demonstrated potential benefits of a large 8.4- or 10-m SLS payload fairing for the science community. Such a fairing would enable the launch of a large aperture (potentially 16-m class) telescope that would be able to make ultra-high-contrast spectroscopic observations of exoplanets. Such a capability would address a need identified in the 2013 NASA astrophysics roadmap, “Enduring Quests, Daring Visions.” Concept evaluations of such a project have also identified opportunities for further collaborations between science and human exploration systems in the form of assembly and servicing of an observatory in deep space.

Interest in taking advantage of the mass-lift capability of SLS has been expressed by the Resource Prospector mission, which would land a rover in the lunar polar region to excavate volatiles such as hydrogen, oxygen, and water from the moon. Discussions between the SLS Program and the Resource Prospector team have focused on the possibility of launching the lander and rover as a co-manifested payload within the Universal Stage Adapter on a crewed flight of Orion, taking advantage of the launch of Orion as an opportunity to deploy the mission to the lunar surface.

While the most obvious mission profiles to benefit from SLS are those with requirements beyond the performance of current launch vehicles, SLS will also offer unique opportunities for smallsats to operate in deep space. The diversity of the 13 CubeSat payloads that will fly within the Orion Stage Adapter on EM-1 demonstrates the broad potential this opportunity provides. (Fig. 11)

CubeSat payloads on EM-1 will include both NASA research experiments and spacecraft developed by industry, international and potentially academia partners. The Human Exploration and Operations Mission Directorate (HEOMD) Advanced Exploration Systems (AES) Division was allocated five payload opportunities on the EM-1 mission.

Near Earth Asteroid (NEA) Scout is a 6U cubesat designed to rendezvous with and characterize a candidate NEA. A solar sail, another innovation to be demonstrated in the cubesat class, will provide propulsion.

Lunar Flashlight will use a green propellant system and will search for potential ice deposits in the Moon’s permanently shadowed craters.

BioSentinel is a yeast radiation biosensor, planned to measure the effects of space radiation on Deoxyribonucleic acid (DNA).

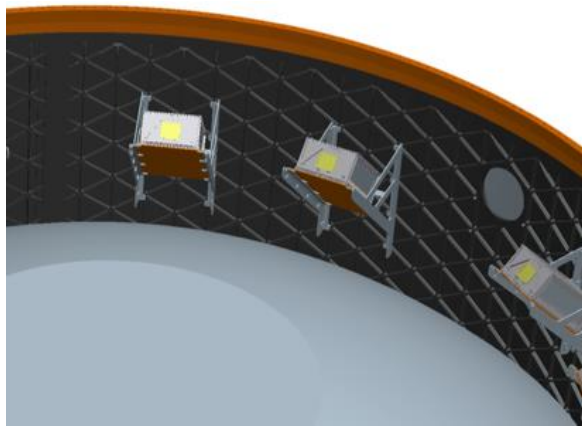


Figure 11. CubeSat accommodations within the Orion Stage Adapter.

Lunar Icecube, a collaboration with Moorehead State University, will prospect for water in ice, liquid, and vapor forms as well as other lunar volatiles from a low-perigee, highly inclined lunar orbit using a compact Infrared spectrometer.

Skyfire, a partnership with Lockheed Martin, is a technology demonstration mission that will perform a lunar flyby, collecting spectroscopy, and thermography data to address questions related to surface characterization, remote sensing, and site selection.

NASA's Space Technology Mission Directorate (STMD) was allocated three payload opportunities on the EM-1 mission. These slots will be filled via the Centennial Challenges Program, NASA's flagship program for technology prize competitions, which directly engages the public, academia, and industry in open prize competitions to stimulate innovation.

The NASA Science Mission Directorate (SMD) was allocated two payload opportunities on the EM-1 mission.

The Cubesat Mission to Study Solar Particles (CuSP) payload will study the sources and acceleration mechanisms of solar and interplanetary particles in near-Earth orbit, support space weather research by determining proton radiation levels during Solar Energetic Particle (SEP) events and identifying suprathreshold properties that could help predict geomagnetic storms.

The LunaH-Map payload will help scientists understand the quantity of H-bearing materials in lunar cold traps (~10 km), determine the concentration of H-bearing materials with 1m depth, and constrain the vertical distribution of H-bearing materials.

The final three payload opportunities for the EM-1 mission were allocated for NASA's international space agency counterparts. The flight opportunities are intended to benefit the international space agency and NASA as well as further the collective space exploration goals.

ArgoMoon is sponsored by ESA/ASI and will fly-along with the ICPS on its disposal trajectory to perform proximity operations with the ICPS post-disposal, take external imagery of engineering and historical significance, and perform an optical communications demonstration.

The EQUULEUS spacecraft sponsored by JAXA will fly to a libration orbit around the Earth-Moon L2 point and demonstrate trajectory control techniques within the Sun-Earth-Moon region for the first time by a nano spacecraft. The mission will also contribute to the future human exploration scenario by understanding the radiation environment in geospace and deep space, characterizing the flux of impacting meteors on the far side of the moon, and demonstrating the future deep space exploration scenario using the "deep space port" at Lagrange points.

The Omotenashi mission sponsored by JAXA will land the smallest lunar lander to date on the lunar surface to demonstrate the feasibility of the hardware for distributed cooperative exploration system. Small landers will enable multi-point exploration, which is complimentary with large-scale human exploration. Once on the lunar surface, the Omotenashi spacecraft will observe the radiation and soil environments of the lunar surface by active radiation measurements and soil shear measurements.

CONCLUSION

With unprecedented mass, volume and C3 capability, NASA's Space Launch System offers unique opportunities for human space exploration, robotic science, and other missions. Currently making progress toward first launch in two years, the SLS Program is already working toward production of an evolvable vehicle that will be the workhorse of NASA's Proving Ground missions in the 2020s and enable human missions to Mars in the 2030s.