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NASA's Space Launch System: Deep Space Access for CubeSats

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Abstract

NASA is embarking on a new generation of missions to the Moon, known as the Artemis program. The Agency's new super heavy-lift launch vehicle, the Space Launch System (SLS), is a critical enabling capability for these efforts, which will serve as a proving ground for future crewed expeditions to Mars. SLS is designed to return astronauts to the Moon in the Orion spacecraft and to launch more mass and provide more volume for critical payloads than commercially available vehicles, giving NASA a unique asset for deep space exploration. When performance margin and volume is available, as it is on the first flight, Artemis I (previously Exploration Mission-1), SLS can offer CubeSats access to deep space, beyond Earth's orbit. The Artemis I flight has 13 6U (14 kg) CubeSats manifested, and the Program is currently accepting proposals for 6U and 12U payloads for the Artemis II flight through the agency's CubeSat Launch Initiative (CSLI) program. Proposals from U.S.-based payload developers to fly on Artemis II will be accepted through CSLI until November 4, 2019. When ridesharing on SLS deep space missions, CubeSats must demonstrate they will not interfere with primary mission objectives. The 13 Artemis I CubeSats that hail from industry, academia, NASA and its international partners represent an array of exciting deep space science investigations and technology demonstrations that may help inform future Artemis missions. The initial SLS Block 1 vehicle for the Artemis I flight is fully manufactured; several elements are complete and have been delivered to the Exploration Ground Systems (EGS) Program at Kennedy Space Center (KSC), which has responsibility for integrating and launching the SLS and Orion stack. Completed elements of the Artemis I vehicle include the Orion Stage Adapter (OSA), which houses the 13 Artemis I CubeSats. With the Artemis I flight hardware and software nearing completion, work is in progress for the second Block 1 launcher, designated for the crewed Artemis II flight. Hardware is being manufactured for every element of the Artemis II vehicle. In this paper, the author will review the status of the Artemis I vehicle and the payloads manifested for the initial flight. Information on the Secondary Payload Deployment System (SPDS) that the SLS Program provides to payload developers will also be included.

Keywords: NASA, Space Launch System, heavy-lift, CubeSats, Artemis I, Artemis II

Acronyms/Abbreviations

Space Launch System (SLS), CubeSat Launch Initiative (CSLI), Exploration Ground Systems (EGS), Orion Stage Adapter (OSA), Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA), Space Shuttle Main Engines (SSMEs), Exploration Upper Stage (EUS), Interim Cryogenic Propulsion Stage (ICPS), Delta Cryogenic Second Stage (DCSS), United Launch Alliance (ULA) trans-lunar injection (TLI), Universal Stage Adapter (USA), Mobile Launcher (ML), Secondary Payload Deployment System (SPDS), Stennis Space Center (SSC), commercial-off-the-shelf (COTS). thrust vector control (TVC), Marshall Space Flight Center (MSFC), Ames Research Center (ARC), Strategic Knowledge Gaps (SKGs), Foreign Object Debris (FOD), Deep Space Network (DSN), radio frequency (RF), avionics unit (AU).

1. Introduction

NASA is executing an ambitious timetable for returning to the Moon [1], known as the Artemis program. The agency remains committed to human exploration of Mars, and returning NASA's human exploration program to the Moon in the 21st century will serve as a proving ground for numerous new technologies needed to enable human exploration of the Red Planet. The super heavy-lift Space Launch System (SLS), with unrivalled capability to lift more mass and provide more volume for strategic payloads is the backbone for NASA's Moon to Mars exploration missions (see Figure 2). The vehicle has a planned upgrade path that will enable human exploration of Mars and game-changing science missions to be launched deep into the solar system. The Gateway lunar outpost and the Orion spacecraft will also play a crucial role in returning NASA's human spaceflight program to the Moon. Orion will enable astronauts to stay in deep space up to 21 days at a time in the spacecraft; it can stay docked to Gateway up to six months. Gateway will give NASA and its partners a platform from which to stage lunar sorties and science missions. Upgraded ground processing and launch facilities at Kennedy Space Center (KSC) are preparing to integrate and launch SLS and Orion to deep space.

CubeSats have a key role to play in the Artemis Program by identifying resources that can be exploited *in situ*, demonstrating new technologies and testing communication. Several CubeSats flying on Artemis I [see Table 1] will be returning valuable data that, if successful, may inform future Artemis missions.

Figure 2. NASA's deep space exploration system, the Space Launch System (SLS) and Orion, launching from Kennedy Space Center, can provide rideshare opportunities for CubeSats.

2. SLS: Evolvable Launch Capabilities for Artemis and Beyond

Designed for a new generation of exploration, SLS will safely send crews in Orion to the Moon and reliably launch NASA's flagship science payloads deep into the solar system. Available in crew and cargo configurations, the vehicle's planned upgrade path will culminate in a launcher of unrivalled lift and payload capacity compared to commercial vehicles (see Figure

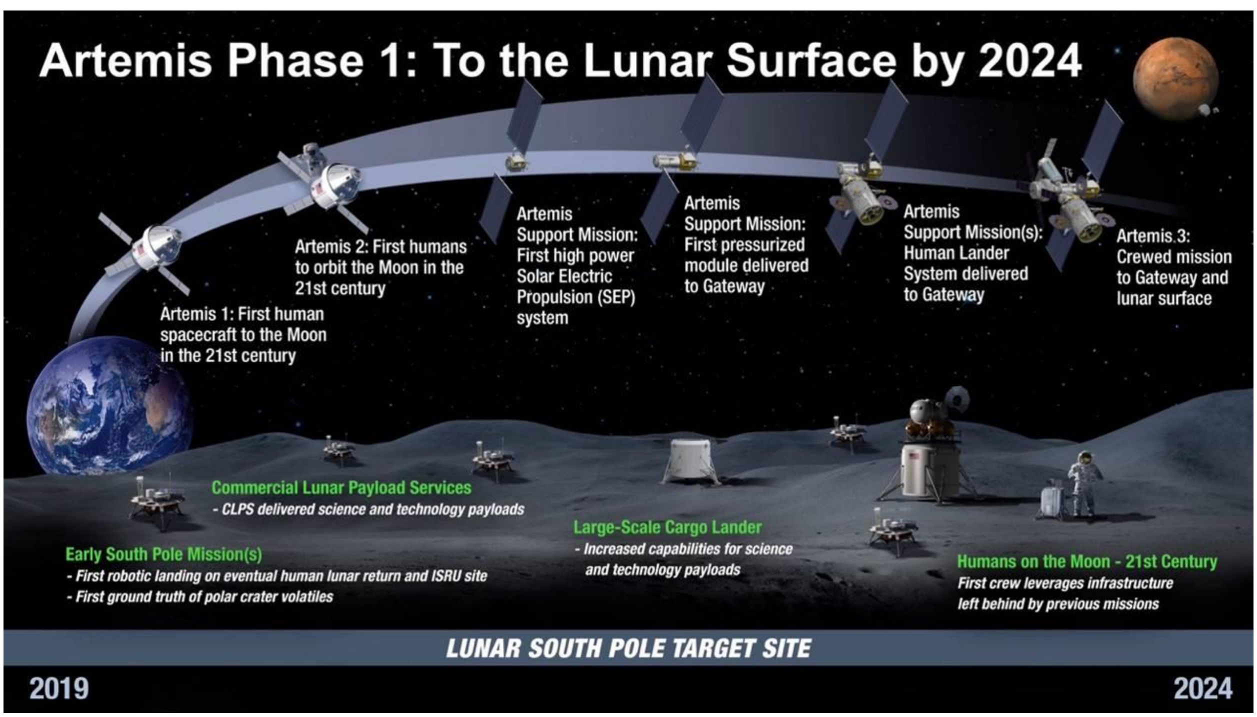

Figure 1. NASA's plan to return astronauts to the lunar surface by 2024 includes three SLS/Orion missions, which can include CubeSats.

3).

SLS is built on a proven, well-understood and extensively tested propulsion system. SLS leverages the space shuttle solid rocket boosters and RS-25 liquid hydrogen (LH2) and liquid oxygen (LOX) engines (formerly the Space Shuttle Main Engines [SSMEs]). These elements have been modified to provide more thrust; the RS-25s have also been adapted to operate in more extreme environments of SLS compared to the shuttle.

A new development, the SLS core stage, includes the LH2 and LOX propellant tanks, avionics and housing for the four RS-25 engines. The Interim Cryogenic Propulsion Stage (ICPS) provides in-space propulsion for the Block 1 vehicle. The ICPS is a modified Delta Cryogenic Second Stage (DCSS), built by United Launch Alliance (ULA) and Boeing. With the ICPS, SLS Block 1 in the crew configuration will lift at least 26 metric tons (t) to trans-lunar injection (TLI). For Block 1 flights, CubeSats are stowed in the Orion Stage Adapter (OSA), which connects SLS to Orion's spacecraft adapter. The SLS program supplies a Secondary Payload Deployment System (SPDS) in the OSA for CubeSat deployment.

NASA plans to fly the Block 1 crew variant for the Artemis I uncrewed test flight and the Artemis II crewed mission. For Artemis II, four crew members in Orion will embark on a lunar flyby free-return mission. The Artemis II crew will surpass the crew of the Apollo 13 flight and become record-holders for traveling farthest from Earth.

All SLS flights will be processed by EGS at KSC, with the vehicle integrated on the Mobile Launcher (ML), which has been upgraded and renovated to service SLS Block 1 in both crew and cargo configurations. Similar to the space shuttle and the Saturn V vehicles, the SLS stack will be assembled on the ML in the iconic Vehicle Assembly Building (VAB) at KSC (see Figure 1). The vehicle will launch from launch complex 39B at KSC.

Following the Block 1 flights, the vehicle will evolve to Block 1B and incorporate a more powerful upper stage. The four-engine LH2/LOX Exploration Upper Stage (EUS) will enable Block 1B to lift at least 34 t to TLI in its crew configuration and at least 37 t in the cargo configuration. The Block 1B cargo configuration can accommodate large-diameter payloads in an 8.4 m-diameter cargo shroud in varying lengths to provide unprecedented volume. For CubeSat payloads, Block 1B will have volume available in the Universal Stage Adapter (USA), which connects the upper stage to Orion on the Block 1B crew variant (see Figure 3).

For Mars-enabling capabilities, the ultimate SLS variant, Block 2, will incorporate upgraded boosters to lift at least 45 t to TLI. Engineers are studying larger-

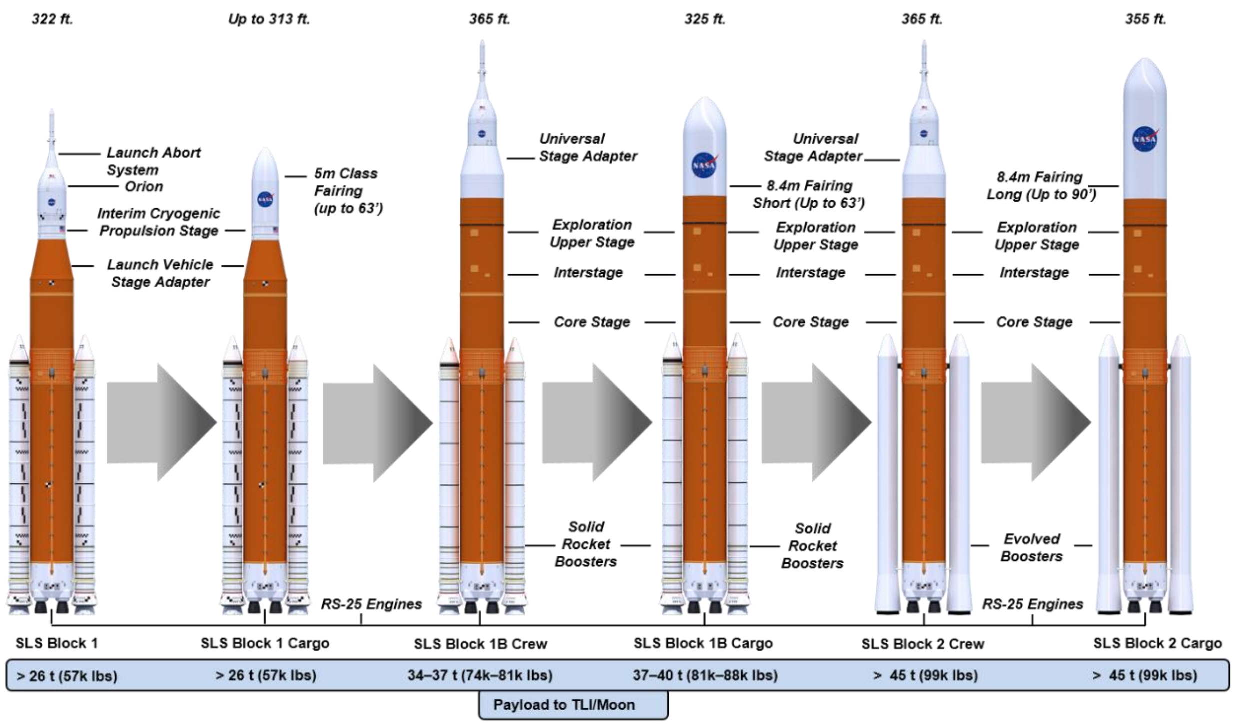

Figure 3. SLS will evolve to progressively more powerful variants, providing NASA with a unique space asset for the most demanding human and robotic deep space missions.

diameter fairings in longer lengths for this vehicle, which can launch habitat modules, landers, rovers and other infrastructure for emplacement in Martian orbit or on the surface prior to the arrival of crew.

CubeSats in 6U and 12U form factors, as well as accommodations for other small payloads, such as Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA)-class, are currently being evaluated for the Block 1B and Block 2 vehicles.

3. Artemis I CubeSats overview

For the first flight of SLS and Orion, NASA allotted 13 of 17 possible slots for 6U form factor payloads, weighing no more than 14 kg, to ride along on the test flight and be deployed to deep space. In addition to the opportunity to reach deep space, SLS offers CubeSat payload developers the opportunity to include propulsion systems on their payloads.

Several Artemis I CubeSats are performing exciting research in deep space that can contribute to future robotic and human lunar missions. BioSentinel, a payload from NASA's Ames Research Center (ARC), aims to develop a biosensor that will evaluate the impact of deep space radiation on living organisms over long durations beyond low-Earth Orbit (LEO). BioSentinel uses yeast to carry out this study, which requires a deep space environment.

LunaH-Map, developed by Arizona State University, will map hydrogen in permanently shaded craters near the lunar South Pole. NASA has identified Shackleton Crater, near the South Pole, as its preferred lunar landing site partially because of the discovery of water ice in its permanently shadowed crater [2]. Areas such as this are considered high-priority influences for future surface activities; data returned by LunaH-Map could be prove beneficial. Similarly, Morehead State University's Lunar IceCube payload will search for water in solid, liquid and vapor states from an orbit about 100 km over the lunar surface. Human or robotic explorers may be able to exploit water ice identified by Lunar IceCube for any number of needs, including life support and propellant production. Lockheed Martin's LunIR payload will use a miniature high-temperature Mid-Wave Infrared (MWIR) sensor to characterize the lunar surface, which could assist in future lander site selection.

CubeSats flying on SLS missions must not interfere with the primary mission, which is a thorough systems check of ground processing and launch facilities, as well as testing of SLS and Orion in a flight environment. To prepare for flight, payload developers work with NASA through a series of payload safety reviews to ensure CubeSats cause no harm to the primary mission or the vehicles. Payload safety reviews are phased over time and cover payload handling and physical processing hazards, radio frequency (RF) interference, possible ascent hazards, debris characteristics for input to unique range safety data, joint loads and environments, payload re-contact analysis (nominal mission scenarios) and more.

In addition, payload developers are responsible for securing RFs and arranging any ground communication services (i.e. amateur radio, near-Earth network, Deep Space Network (DSN), etc.). Once mission managers establish frequencies that SLS and Orion will use, payload developers must verify their frequencies do not interfere with vehicle frequencies.

4. CubeSat deployments on SLS Block 1

Artemis I is planned as an approximately 25-day mission that will include an extended stay in high-Earth orbit for a thorough systems checkout before

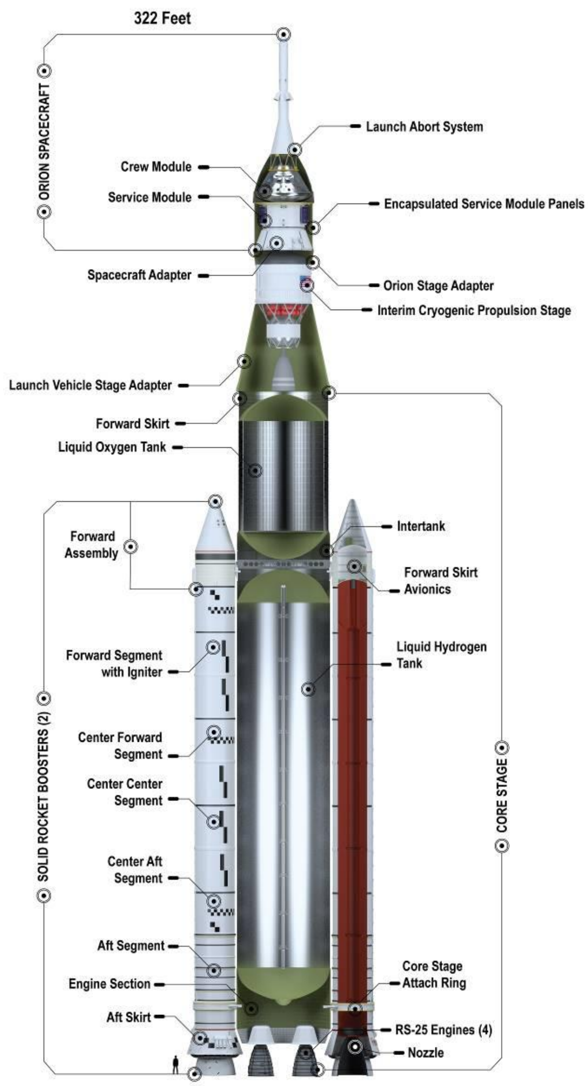

Figure 4. Elements of the SLS Block 1 crew vehicle.

committing to TLI. The ICPS will provide the burn to send Orion to TLI. After separation from Orion, the stage will perform a series of maneuvers to insert itself into a heliocentric disposal trajectory. The ICPS will be pointed at a 55-degree beta angle to the sun to give the payloads the best thermal conditions possible. The stage will put itself into a 1 revolution per minute (rpm) barbecue roll. The stage will vent any remaining hydrazine, take a final set of readings, downlink them and shut down. Prior to final shutdown, the stage will send an activation signal to the SPDS, initiating the CubeSat deployment process.

The deployment window for the CubeSats is near the completion of ICPS disposal maneuvers to about 10 days post-launch. To give payload developers an idea of the timelines involved and some deployment windows that could be beneficial for missions, SLS engineers identified several "bus stops" from which payload developers can choose to release payloads.

Thermal conditions are one of several factors each payload developer considered when determining which bus stop to use for payload deployment. In addition to thermal environments, payload developers considered flight time to the Moon, which affects propellant usage; radiation conditions (see Figure 6), mission goals, ICPS attitude stability and more. After considering these factors, each payload developer selected its final bus stop, or deployment location.

For both Artemis I and II Block 1 flights, the SLS Program supplies mounting brackets, cable harnesses and an avionics unit (AU). The AU is activated after the TLI burn and near the completion of the disposal maneuvers. The AU receives simple discrete signals from the ICPS to start a pre-coordinated, pre-loaded, autonomous deployment sequence; it has a battery life of 10 days after on-orbit activation. For 6U CubeSats, a vibration isolation/mitigation system is also provided.

Payload dispensers are commercial-off-the-shelf (COTS) models. The SPDS mounting bracket design includes connector mounting and dispenser interfaces. The 6U brackets are designed to hold up to 60 lbs.; most payloads with the COTS dispenser are expected to weigh about 47 lbs. Based on the maximum allowable payload mass for a 6U dispenser, an ejection rate of 3.9 +/ -0.2 feet/sec (1.2 +/- 0.06 m/sec) is anticipated.

Technicians at MSFC installed the SPDS in the OSA and tested the avionics prior to shipping to EGS. Once payloads are mounted in the OSA, payload batteries can be charged. Once batteries are charged and the OSA with the payloads installed moves to the VAB for stacking, no additional access to the payloads is possible.

5. Artemis I Payload Manifest

Payload developers from industry, government, academia and international partners have 6U CubeSats manifested on Artemis I. Three payloads are competing for prize money in the CubeQuest Challenge, part of NASA's Centennial Challenges. Outside of the three CubeQuest missions, which earned slots based on their performances in qualifying ground tournaments, the remaining ten CubeSats were selected based on the possibilities of returning data to address identified Strategic Knowledge Gaps (SKGs) [3]. Mission planners will use a more focused set of criteria to evaluate proposals for CubeSats to fly on Artemis II, choosing payloads that will support the Artemis program by addressing lunar or Martian SKGs that will support returning humans to the Moon and exploring onward to Mars. See Table 1 for a complete listing of CubeSat missions manifested on Artemis I.

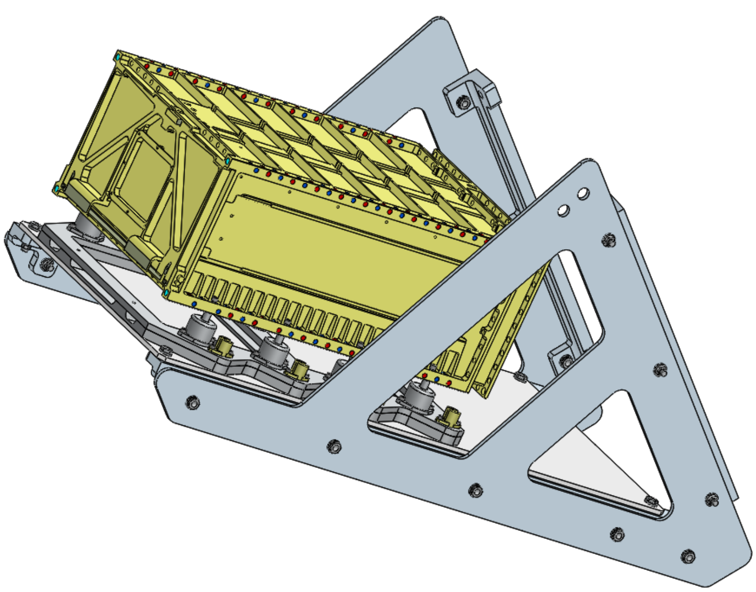

Figure 5. The SLS Secondary Payload Deployment System (SPDS) includes mounting brackets, a vibration isolation system and a commercial-off-the-shelf (COTS) dispenser.

Table 1. Artemis I SLS Payload Manifest.

Payload	Developer(s)	Sponsor	Destination	Mission
ArgoMoon	Argotec	Agenzia Spaziale Italiana (ASI)	Geocentric orbit with high eccentricity and apogee close to the Moon	Photograph the ICPS, CubeSat deployment, the Earth and Moon using HD cameras and advanced imaging software
Biosentinel	NASA Ames, NASA Johnson, Loma Linda University Medical Center, University of Saskatchewan	NASA Advanced Exploration Systems (AES)	Heliocentric orbit via lunar flyby	Use yeast as a biosensor to evaluate the effects of ambient space radiation on DNA
Cislunar Explorers	Cornell University	NASA Cube Quest Challenge, sponsored by NASA's Science Technology Mission Directorate (STMD) Centennial Challenges	Lunar orbit	Demonstrate use of an inert water-based propulsion system for lunar gravity assists and capture in lunar orbit; compete in NASA's Deep Space Derby
CubeSat to Study Solar Particles (CuSP)	Southwest Research Institute, NASA Goddard	NASA Science Mission Directorate (SMD)	Deep space	Study the sources and acceleration mechanisms of solar and interplanetary particles in near-Earth orbit
EQUilibriUm Lunar-Earth point 6U Spacecraft (EQUULEUS)	University of Tokyo	Japanese Aerospace Exploration Agency (JAXA)	Earth-Moon L2 point	Demonstrate trajectory control techniques within the Sun-Earth-Moon region and image Earth's plasmasphere
Lunar IceCube	Morehead State University, NASA JPL, NASA Goddard, BUSEK	NASA Next Space Technologies for Exploration Partnerships (NextSTEP)	Lunar orbit	Search for water (and other volatiles) in ice, liquid and vapor states using infrared spectrometer
Lunar Flashlight	NASA JPL	NASA AES	Lunar orbit	Search for ice deposits using near-infrared band lasers
Lunar-Polar Hydrogen Mapper (LunaH-Map)	Arizona State University	NASA SMD	Lunar orbit	Perform neutron spectroscopy to characterize abundance of hydrogen in permanently shaded craters
LunIR	Lockheed Martin Space Systems	NASA NextSTEP	Heliocentric orbit via lunar flyby	Use a miniature high-temperature Mid-Wave Infrared (MWIR) sensor to characterize the lunar surface
Near Earth Asteroid (NEA) Scout	NASA Marshall	NASA AES	NEA within ~1.0 AU of Earth	Detect target NEA, perform reconnaissance and close proximity imaging
Outstanding MOon exploration Technologies	Institute of Space and Astronautical Science (ISAS)/JAXA	JAXA	Lunar surface	Develop world's smallest lunar lander and observe lunar radiation environment

demonstrated by Nano Semi-Hard Impactor (OMOTENASHI)				
Team Miles	Miles Space, LLC	NASA Cube Quest Challenge	Deep space	Demonstrate propulsion using plasma thrusters; compete in NASA's Deep Space Derby
University of Colorado-Earth Escape Explorer (CU-E^3)	University of Colorado in Boulder	NASA Cube Quest Challenge	Deep space	Demonstrate use of solar radiation pressure for propulsion; compete in NASA's Deep Space Derby

5.1 Vicinity of bus stop one

Payloads are deployed in one-minute intervals to reduce likelihood of contact. The first bus stop, about four hours post-launch, is between Earth's two Van Allen Belts. Two missions from JAXA, OMOTENASHI and EQUULEUS, will deploy at this time. The OMOTENASHI CubeSat will use a solid rocket motor to attempt a lunar landing. If successful, OMOTENASHI will provide JAXA with two firsts: developer of the smallest lunar lander to date and the fourth country to successfully land on the Moon.

Lunar Flashlight, BioSentinel, ArgoMoon, Cislunar Explorers and Lunar IceCube also plan to deploy at bus stop 1. About 90 minutes after the ICPS clears the first Van Allen Belt, Near Earth Asteroid (NEA) Scout, a NASA Marshall Space Flight Center (MSFC) mission equipped with a solar sail to rendezvous with an asteroid, will deploy.

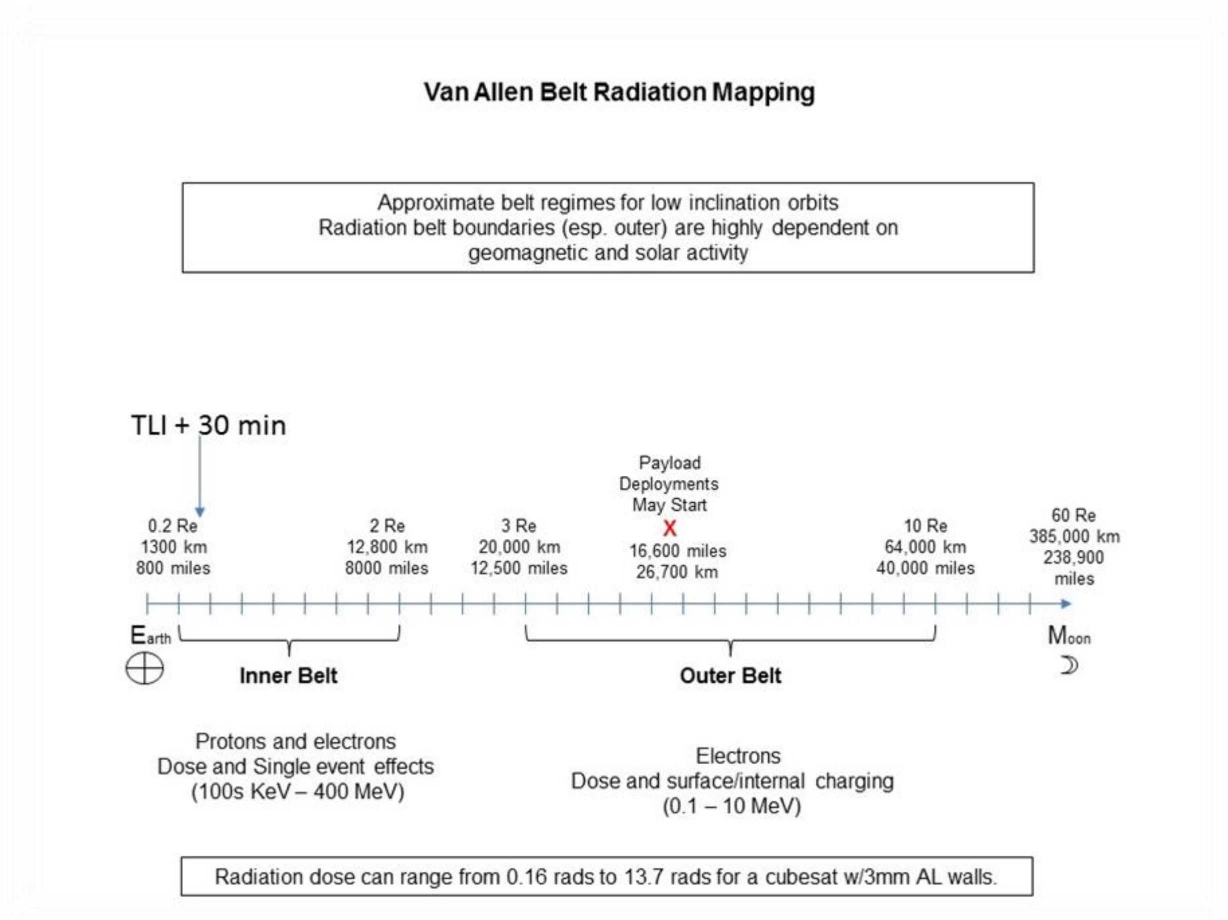

Figure 6. Radiation exposure to Artemis I payloads from the first deployment opportunity to the Moon.

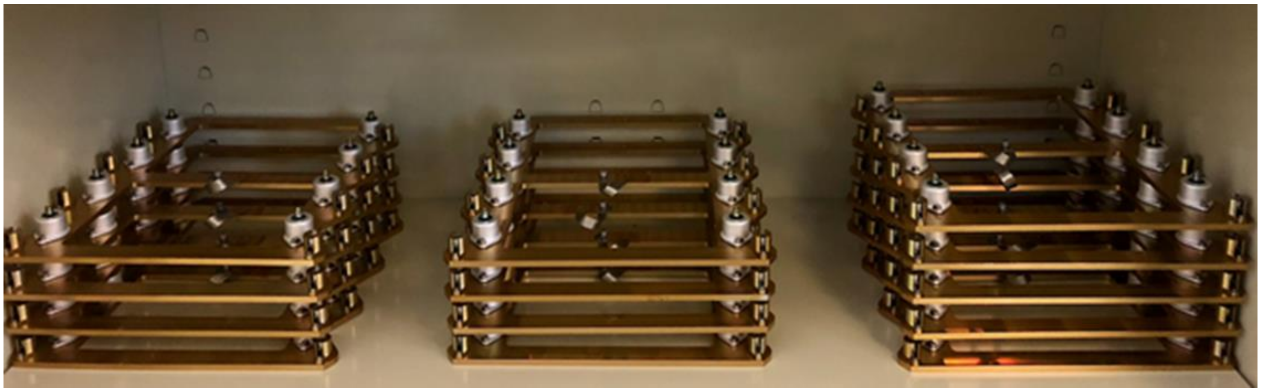

Figure 7. Vibration mitigation system for Artemis I 6U CubeSats.

5.2 Vicinity of bus stop two

After the ICPS has cleared both radiation belts, the LunaH-Map payload will be released. About one hour after clearing the radiation belts, at bus stop two, Lockheed Martin's LunIR spacecraft will deploy. Using a miniature high-temperature Mid-Wave Infrared (MWIR) sensor to collect spectroscopy and thermography data, LunIR will provide data related to surface characterization, remote sensing and site selection for lunar future missions.

5.3 Vicinity of bus stop five

At bus stop 5, about 12 hours after the ICPS passes the Moon and uses its gravity to enter heliocentric orbit, the final three smallsats will be released: *CuSP*, Team Miles and CU-E[3]. At this time, no payload developers have chosen to deploy payloads at bus stops three or four.

6. Artemis II Opportunities for CubeSats

For the second flight of SLS and Orion, Artemis II, mission planners expect to be able to accommodate a limited number of 6U and 12U form factor payloads. Similar to Artemis I, payloads selected for the Artemis II flight should address SKGs. Specifically, the agency is looking for smallsat research missions that will reduce risk on future human spaceflight missions. For Artemis II, outbound travel to the Moon will be about five days. At closest approach to the Moon, the ICPS will pass approximately 260 km from the lunar surface.

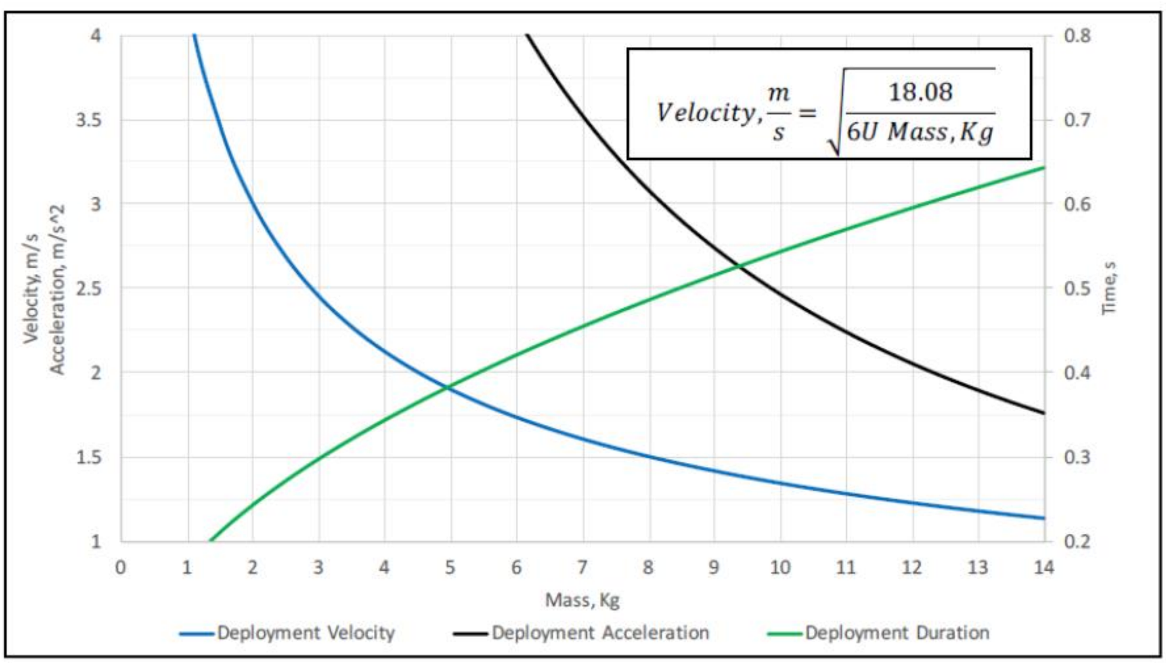

Figure 8. Anticipated ejection velocity of 6U payloads released from SLS SPDS on Artemis I.

Because Artemis II is also a Block 1 flight, payloads will be stowed in the OSA, as in the Artemis I flight. The SPDS provided will be similar.

7. Artemis I Vehicle Status

The first SLS Block 1 vehicle is fully manufactured, with several elements complete and delivered to EGS, including the OSA with the SPDS for the 13 Artemis I 6U CubeSats (see Figure 10). In addition to the OSA, the Artemis I ICPS is complete and delivered to EGS. The SLS solid rocket boosters, based on the space shuttle boosters but larger and more powerful, are largely complete for the first mission. The solid-fuel motors, with new asbestos-free insulation, have five propellant segments compared to the shuttle's four-segment boosters. The extra propellant segment gives the boosters 20 percent more thrust; each provides 3.6 million pounds of thrust. The motors for the Artemis I flight are complete and will ship to KSC in the coming months. Forward and aft sections of the boosters, including the thrust vector control (TVC) systems in the aft skirts, are nearing completion (see Figure 9).

The four RS-25 engines designated for the Artemis I flight are also complete. The SLS Program has 16 RS-25s remaining from the Space Shuttle Program. The engines have been upgraded with new controllers. A series of hot-fire tests at Stennis Space Center (SSC) has qualified the engines to operate in the SLS environments. The four RS-25s for Artemis I were delivered to Michoud Assembly Facility near New Orleans earlier in 2019. Technicians will integrate the RS-25 engines into the core stage in the final months of 2019.

The 212-foot core stage, comprising an engine section and boat tail assembly where the RS-25s are housed; the LH2 tank; an intertank; the LOX tank; and a forward skirt where flight computers are installed, is not only a new development – it will also be the tallest rocket stage ever to fly. Manufacturing such a massive stage for the first time has presented several challenges for the team to work through. Most of these first-time-build technical difficulties have been solved and the five major components are structurally joined (see Figure 12). Following engine installation and final checkouts, the stage will ship to SSC for the Green Run test campaign.

NASA's barge Pegasus will transport the enormous stage from Michoud to SSC, where the B-2 test stand has been upgraded, activated and is ready for the stage. Pegasus was lengthened and reinforced to transport the SLS core stage. Crews removed a 115-foot section of the barge and replaced it with a 165-foot section specially designed to increase the weight Pegasus can ferry. Length of the barge increased from 260 feet to 310 feet.

Figure 9. An aft skirt for the Artemis I solid rocket boosters is nearly complete at Kennedy Space Center (KSC). Four booster separation motors are visible.

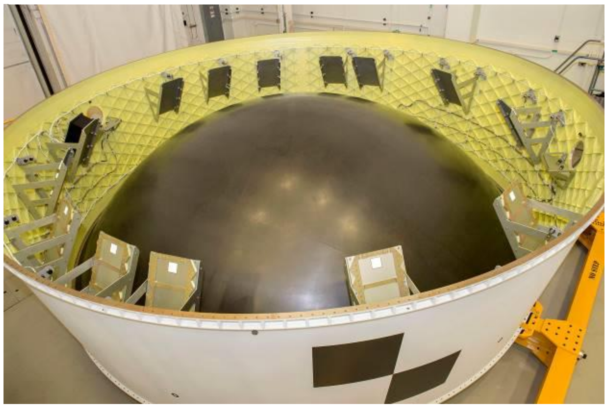

Figure 10. The Orion Stage Adapter (OSA) with Secondary Payload Deployment System (SPDS) has accommodations for 13 6U CubeSats on the Artemis I flight.

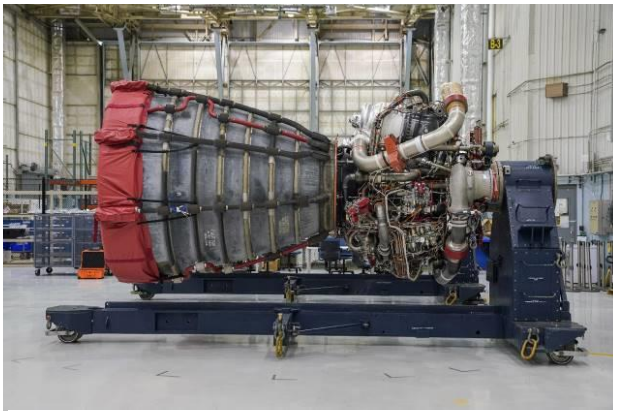

Figure 11. Completed RS-25 engine ready for installation in the Artemis I core stage.

Figure 12. Technicians at Michoud Assembly Facility near New Orleans have structurally joined the SLS Core stage for the Artemis I flight.

Green Run will feature a number of “firsts” for SLS. Green Run will be the first time the propellant tanks are filled; the first end-to-end flow test of propellants and other fluids through the complete stage; the first operational test of stage avionics; and the first time the four RS-25 engines are fired simultaneously.

Green Run as currently baselined is a combination of both qualification and acceptance testing. The test series will validate the core stage design, design models and workmanship and verify the stage is ready to ship to KSC for final processing and integration. In addition to the hot-fire testing, the entire test program as currently outlined involves a number of prerequisite tests, including vibration testing, power-on, leak and functional checks, hydraulics and TVC, safing, simulated countdown and “wet dress rehearsal” during which propellants are flowed through the stage but not ignited.

8. Conclusion

Artemis I is the first in a series of exciting missions to the Moon. Manufacturing is complete on the initial SLS Block 1 vehicle, which will carry 13 6U CubeSats along on the test flight. Several elements, including the OSA where the CubeSat payloads will be mounted, are complete and delivered to EGS. The core stage, an all-new development, will ship to SSC in 2020 for a Green Run test of avionics, tanking and engines. Following Green Run, the stage will be refurbished and shipped to KSC where the vehicle will be stacked with Orion and launched on an approximately 25-day test flight. CubeSats will be released into deep space once Orion has separated from the vehicle and the ICPS has performed disposal maneuvers.

NASA is accepting proposals through November 4, 2019 for CubeSats to fly on the second flight of SLS and Orion, Artemis II. This flight will send four crew members in Orion on a lunar free-return mission. Heliocentric disposal targets are more challenging on this flight and fewer CubeSats are expected to be manifested. It is possible that the program will choose 12U as well as 6U payloads to fly on Artemis II. Tentatively the maximum mass of a 12U Cubesat is 20 kg. U.S.-based payload developers can submit a proposal for a payload to fly on Artemis II through the CSLI Program [4]. The SPDS and payload safety review requirements for the Artemis II flight will be similar to the Artemis I mission. NASA will prioritize missions that address lunar and Martian SKGs and help reduce risk for future Artemis missions.

Although SLS will be the largest, most powerful launcher since the Saturn V and is primarily designed to lift Orion and large science missions, mission planners hope to offer rideshare opportunities to smallsats whenever performance and volume are available, as on the Artemis I mission. By riding along on SLS, CubeSats have the ability to reach deep space and perform exciting science and technology demonstration missions, including testing propulsion systems.

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