NASA's Space Launch System and Deep Space Opportunities for Smallsats

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Designed to provide the significant capability required for human deep-space exploration, the National Aeronautics and Space Administration's Space Launch System (SLS) also provides an exceptional opportunity for lower-cost deep-space science in the form of small-satellite (smallsat) secondary payloads. This opportunity will be leveraged beginning with the rocket's first flight; a launch of the SLS's Block 1 configuration, capable of delivering >26 metric tons (t) to Trans-Lunar Injection (TLI), which will see the Orion crew vehicle travel around the Moon and return to Earth. On that flight, SLS will also deploy 13 6U-class CubeSat secondary payloads to multiple destinations including deep space. Preparations are already under way for future vehicle configurations, with the more capable Block 1B, able to deliver 40 metric tons to TLI. That configuration will have the capability to carry large payloads co-manifested with the Orion spacecraft, or to utilize an 8.4-meter (m) fairing to carry payloads several times larger than are currently possible. SLS will evolve to its full Block 2 configuration, with a TLI capability of >45 metric tons. This paper will provide a status of the SLS development and outline the progress being made toward flying smallsats on SLS, and discuss future opportunities for smallsats.

Key Words: SLS, NASA, Smallsat, CubeSat, EM-1

1. Introduction

Designed to return astronauts to the Moon in the Orion crew vehicle and to launch into deep space the largest space infrastructure and robotic payloads, Space Launch System (SLS) is the launch vehicle that will make this happen. The vehicle's flexible architecture and block configurations make available a progressively more powerful and capable family of super heavy-lift launchers for the most demanding missions.

Fig. 1. In addition to sending the Orion crew vehicle and co-manifested payloads on lunar trajectories, SLS opens deep space to smallsats.

The cargo version of SLS can accommodate industry-standard 5m-class or larger 8.4m fairings in a variety of lengths, providing unmatched payload volume.

In addition to SLS's large lift capability(mass/volume), a rare opportunity is provided for lower-cost deep space science for small-satellite (smallsat) secondary payloads. On the first flight of the SLS launch vehicle, Exploration Mission 1 (EM-1), 13 6U-class CubeSat payloads will be deployed. The payloads represent a variety of disciplines including, but not limited to, studies of the Moon, Earth, Sun and asteroids, along with technology demonstrations that could pave the way for even more ambitious (and larger) smallsat missions in the future.

2. Exploration Mission 1

EM-1, the first integrated mission for National Aeronautics and Space Administration's (NASA), new deep space exploration system, will focus primarily on verifying and checking out new spacecraft and ground systems. In addition EM-1 will send 13 smallsats beyond Low Earth Orbit (LEO) for scientific investigations and technology demonstrations. Kennedy Space Center (KSC) is upgrading and modernizing its facilities to launch SLS to send Orion on a 25.5-day mission to a distant retrograde lunar orbit. SLS and Orion's primary mission objectives include validating thermal, control and data systems; testing deep space maneuvers, communications and tracking; demonstrating landing and recovery operations; and testing motion imagery systems. A secondary objective of EM-1 is to deploy the secondary payloads into deep space after the Trans-Lunar Injection (TLI) burn.

For EM-1, mission planners chose the 13 smallsat payloads from a range of industry, academic and international partners as well as from within NASA. Preference was given to missions that will return data and results that may address Strategic Knowledge Gaps, information NASA needs to reduce risk and increase design and effectiveness of future robotic and human space exploration missions. Three additional payloads were selected as part of the Cube Quest competition, administered by NASA's Centennial Challenge

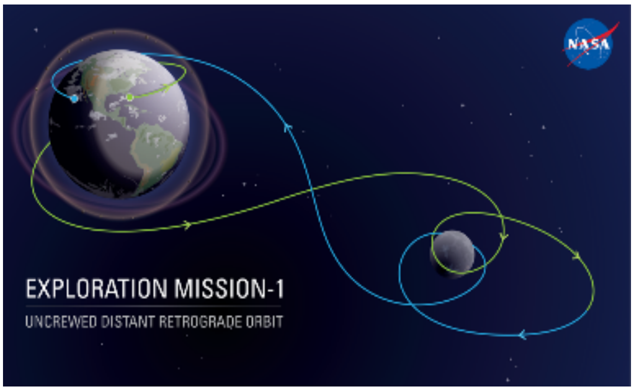

Fig. 3. EM-1, the first mission of NASA's new deep space exploration system, has 13 smallsats on the manifest that will perform a variety of scientific investigations and technology demonstrations.

Program. The competition offers a total of $5 million in prizes to teams that meet the challenge objectives of designing, building and delivering flight-qualified, small satellites capable of advanced operations near and beyond the Moon.

A key requirement imposed on the EM-1 secondary payload developers is that the smallsats do not interfere or represent an unacceptable risk to Orion, SLS or primary mission objectives. To meet this requirement, payload developers must take part in a series of safety reviews with the SLS Program's Spacecraft Payload Integration & Evolution (SPIE) organization, which is responsible for the Block 1 upper stage, adapters and payload integration. In addition to working with payload developers to ensure mission safety, the SLS Program also provides a secondary payload deployment system in the vehicle's Orion Stage Adapter (OSA). The deployment window for the CubeSats will be from the time Interim Cryogenic Propulsion Stage (ICPS) disposal maneuver is complete (currently estimated to require about four hours post-launch) to up to 10 days after launch. This is performed in accordance with five (5) defined "bus-stops" as shown in Figure 3, beginning between the Van Allen radiation

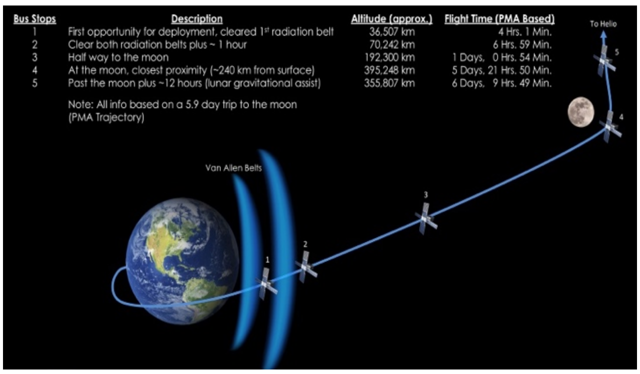

Fig. 2. Providing smallsats with extraordinary access to deep space, SLS presented payload developers with several "bus stops," or deployment opportunities, for the first mission; similar opportunities are expected to be available on future missions.

belts once the Orion spacecraft has separated and is a safe distance away to preclude recontact with a cubesat, to just prior to placing the ICPS in a heliocentric disposal trajectory just past the Moon.

2.1 EM-1 Secondary Payload Manifest

The CubeSat manifested on EM-1 will undertake a diverse variety of experiments and technology demonstrations. Seven payloads will be deployed after the ICPS has cleared the first Van Allen Radiation Belt. JAXA, the Japanese Space Agency, will have two smallsats deploy at the first stop (bus stop 1, Figure 3). The *Outstanding MOon exploration TEchnologies demonstrated by Nano Semi-Hard Impactor (OMOTENASHI)* mission will land the smallest lander to date

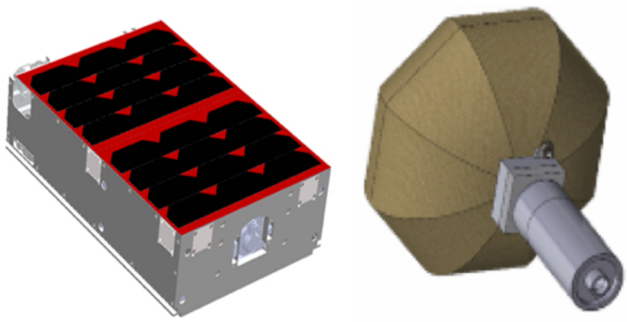

Fig. 4. OMOTENASHI (right) and it's lunar lander with decent motor deployed (left), demonstration of ultra-small Moon landing technologies, manifested on EM-1.

on the lunar surface to demonstrate the feasibility of the hardware for distributed cooperative exploration systems. If this mission is successful, Japan could be the fourth nation to successfully land a mission on the Moon. The other JAXA payload, the *EQUilibriUm Lunar-Earth point 6U Spacecraft (EQUULEUS),* will fly to a libration orbit around the

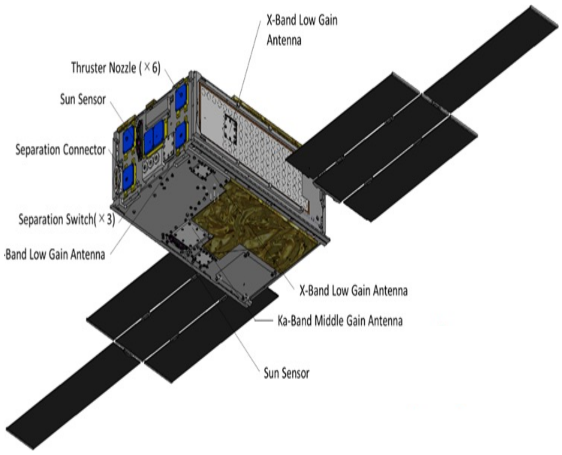

Fig. 5. EQUULEUS technology demonstration in orbital control and science observations, manifested on EM-1.

Earth-Moon L2 point and demonstrate trajectory control techniques within the sun-Earth-Moon region for the first time by a smallsat. *Lunar Flashlight* is a NASA Jet Propulsion Laboratory mission that will look for ice deposits and identify locations where resources may be extracted from the lunar surface. The NASA Ames Research Center-developed *BioSentinel* mission is a yeast radiation biosensor that will measure effects of space radiation on DNA. *ArgoMoon,* sponsored by the Agenzia Spaziale Italiana (ASI), will perform proximity operations with the ICPS post-disposal and record imagery of engineering and historical significance — as well as of the Earth and Moon — by testing an advanced software imaging recognition system using high-definition cameras. Cislunar Explorers, a team from Cornell University in Ithaca, New York, USA, competing in NASA's Cube Quest Centennial Challenge competition, has designed a 6U CubeSat that will split into two smaller spacecraft that will orbit the Moon using a novel propulsion system of inert water to carry out gravity assists and then be captured into lunar orbit. Finally, *Lunar Icecube*, developed by Morehead State University in Kentucky, USA, will search 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.

About 90 minutes after the ICPS clears the first Van Allen Belt, the *Near Earth Asteroid (NEA) Scout*, a NASA Marshall Space Flight Center (MSFC) mission equipped with a solar sail to rendezvous with an asteroid, will be deployed. NEA Scout will gather detailed imagery and observe the asteroid's position in space. After the ICPS has cleared both radiation belts, the *Lunar-Polar Hydrogen Mapper (LunaH-Map)* payload from Arizona State University will be released. LunaH-Map will help scientists understand the quantity of hydrogen-bearing materials in cold traps in permanently shaded lunar craters via low-altitude flybys of the Moon's south pole. About one hour after clearing the radiation belts (bus stop 2, Figure 3), Lockheed Martin's *LunIR* spacecraft, a technology demonstration mission that will perform a lunar flyby, will be deployed. 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.

About 12 hours after the ICPS passes the Moon (bus stop 5, Figure 3) and uses its gravity to enter heliocentric orbit, the final three smallsats will be released. The *CubeSat Mission to Study Solar Particles (CuSP)* from Southwest Research Institute in San Antonio, Texas, USA, 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 suprathermal properties that could help predict geomagnetic storms. Team Miles, of Miles Space, LLC, of Tampa, Florida, USA, another Cube Quest competitor, has a mission that will fly autonomously using a sophisticated onboard computer system. The spacecraft will be propelled by evolutionary plasma thrusters. The final Cube Quest entrant, the *University of Colorado-Earth Escape Explorer (CU-E^3)*, is a CubeSat from the University of Colorado in Boulder, Colorado, USA, that will be use solar radiation pressure rather than an onboard propulsion system.

2.2. Space Launch System Block 1 Vehicle.

EM-1 will use the Block 1 configuration of the SLS launch vehicle. SLS's Block 1 configuration, capable of delivering >26 t to TLI, consists of the core stage, four RS-25 engines, two solid rocket boosters, one upper stage, and two adapters.

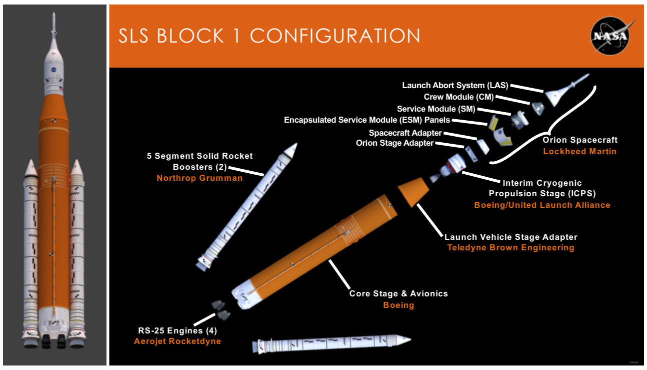

Fig. 6. EM-1 mission to help ready Orion and the launch vehicle for humans will use the SLS Block 1 configuration.

2.3. Block 1 Smallsat Accommodations

To release the payloads, the SLS Program installed a secondary payload deployment system in the OSA that includes mounting brackets for the commercial off-the-shelf (COTS) dispensers, cable harnesses, and an avionics unit. The avionics unit is a standalone controller that controls the release of the secondary payloads. Prior to shipping the completed OSA to the Exploration Ground Systems (EGS)

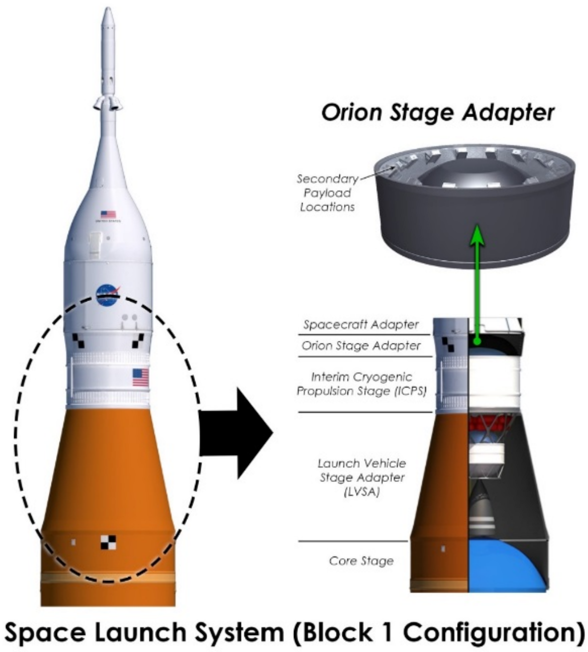

Fig. 7. At the top of the Block 1 configuration, the Orion Stage Adapter has capacity for up to 19 smallsats; the SLS Program provides an integrated deployment system for the payloads.

Program at KSC, engineers at MSFC tested the avionics unit to ensure scripts for controlling bus stop deployments performed as expected. For EM-1, each payload developer is responsible for the payload, the specified dispenser, vibration isolation system and thermal protection.

Before the OSA is stacked on the ICPS in the Vehicle Assembly Building at KSC, the payloads previously integrated in their COTS dispensers will be installed onto the brackets in the OSA. The payloads and the deployment avionics unit's batteries will then be charged. On launch day, the ICPS will be loaded with the upper stage operational parameters for the flight, including data needed for the secondary payload deployment system avionics unit to perform the correct deployment sequence for the mission based on trip time to the Moon and when the payloads need to be deployed to complete their missions.

After the TLI burn and separation of Orion from the ICPS/OSA, and conclusion of most of the ICPS disposal maneuvers, the ICPS will power on the secondary payload deployment system's avionics unit. Then the ICPS will put itself into a one revolution per minute (rpm) roll and be pointed at a 55-degree beta angle to the sun to minimize the thermal environments for the secondary payloads. Once the propellant is spent, the ICPS will take one more set of readings, downlink those readings and shut down. The secondary payload avionics unit can then start deploying the CubeSats.

Another noteworthy benefit SLS provides to the EM-1 CubeSats is the ability to incorporate propulsion systems on the payloads. In most smallsat missions to LEO, CubeSats are restricted from having propulsion systems. CubeSats operating in deep space, on the other hand, require propulsion systems in many mission scenarios. The EM-1 CubeSats employ several types of propulsion systems, including ion, solid, green propellant, solar, pressure, and etc., providing mission developers with the rare opportunity to utilize these small propulsion systems in deep space.

3. Progress Towards First Flight

The progress of the different elements of the SLS Block 1 vehicle that will be used for EM-1 mission will be discussed in the following sections.

3.1. Core Stage

The SLS core stage, the largest ever constructed in terms of both length and volume, consists of an engine section that houses the four RS-25 engines, a liquid hydrogen (LH2) fuel tank, an intertank structure that includes the forward attach points for the solid rocket boosters, the liquid oxygen (LOX) oxidizer tank and the forward skirt, which holds most of the vehicle's avionics. Core stage prime contractor Boeing is manufacturing the stage at NASA's historic Michoud Assembly Facility near New Orleans, Louisiana, USA. Parts of NASA's Saturn V, the Space Shuttle and now SLS have all been manufactured at Michoud. The SLS Program modernized the factory by installing the world's largest spacecraft welding tool, the Vertical Assembly Center. That investment has paid off as weld confidence articles, structural test articles and flight hardware have all been manufactured for EM- 1. Boeing has even begun manufacturing the core stage for the second SLS mission.

The EM-1 core stage engine section has completed welding; major subassembly and integration work is underway. Technicians are installing the Thrust Vector Control (TVC) system, boat tail assemblies, pumps, manifolds, ducts, cables, harnesses and instrumentation for flight. The EM-1 LH2 tank, which will hold 537,000 gallons of cryogenic fuel, has been constructed and proof-tested. At the time of writing, the LH2 tank had undergone a thorough cleaning process and been primed. After priming, major work on the tank includes applying the thermal protection system, similar to the thermal protection used on the Space Shuttle external tank.

The EM-1 intertank will measure 6.7 m long, and will connect the LH2 tank below it to the LOX tank above it. The intertank serves as the forward attach point for the five-segment solid rocket boosters and contains the supporting

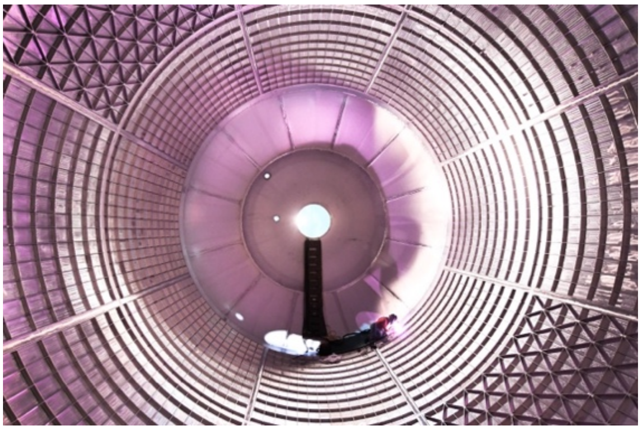

Fig. 8. Technicians welded the 39.6 m LH2 tank on the world's largest spacecraft welding tool, the Vertical Assembly Center, at Michoud Assembly Facility.

thrust structure needed to handle the loads the boosters will impart. To handle the enormous booster- induced thrust loads plus the stresses of the rocket above and below it, the intertank is the thickest core stage structure and is bolted rather than welded. The intertank consists of eight panel sections and more than 7,500 high-strength bolts.

The EM-1 LOX tank required thicker walls than the LH2. That tank was successfully manufactured and has been sprayed with thermal protection system. Robotic acreage sprays were possible on the barrel section, but manual spraying was required for the domes. Technicians are installing sensors and cable harnesses on the EM-1 forward skirt and testing is underway on the avionics system and harnesses.

3.2. RS-25 Engines

The four RS-25 engines, manufactured by prime contractor Aerojet Rocketdyne, are of Space Shuttle heritage, and upgraded with the latest technology. The engines for EM-1 are complete and ready for integration with the SLS core stage later in 2018. The RS-25 engines will generate 512,000 lbs. of thrust each and operate for about eight minutes. The RS-25 was selected for SLS based on its power, its successful performance over 135 Space Shuttle missions and its well-understood characteristics over more than a million seconds of ground and flight operating time.

The SLS Program is using flight-proven RS-25s and in addition to the new, updated controllers and software, new nozzle insulation is necessary to meet greater thermal protection requirements due to the engines' location nearer the booster nozzles. For SLS, the engines will operate at 109 percent thrust versus the 104.5 percent that was standard for Space Shuttle missions to LEO.

The NASA-Aerojet Rocketdyne team continues to push the world's most proven rocket engine to new heights. During a recent hot-fire test at NASA's Stennis Space Center, a development engine achieved a record 113 percent thrust. In addition, NASA and Aerojet Rocketdyne have restarted production of the RS-25 engines for the fifth mission and beyond and are also working to make the engines more affordable and easier to manufacture. Part of this initiative to reduce costs and labor includes using additively manufactured rocket engine parts. In December 2017, a 3D-printed pogo accumulator was tested on a development engine. The additively manufactured parts and other process improvements aim to reduce the cost of future RS-25s by 30 percent. In the additive manufacturing process used to build the pogo accumulator, more than 100 welds were eliminated, reducing costs by nearly 35 percent and production time by more than 80 percent. Initial reports show the 3D-printed hardware performed as expected, opening the door for more additively manufactured components scheduled for future tests.

Fig. 9. All four EM-1 RS-25 engines have been tested and verified; they are ready for integration into the core stage and flight.

3.3. Solid Rocket Boosters

The SLS solid rocket boosters, built by prime contractor Northrop Grumman, are the largest ever built for flight. The five-segment solid-fuel motors provide more than 7.2 million pounds of thrust, more than 75 percent of total vehicle thrust at liftoff. With 25 percent more propellant than the Space Shuttle-era booster on which it is based, the SLS boosters burn through more than six tons of polybutadiene acrylonitrile (PBAN) each second during their approximately two-minute flight.

All ten EM-1 motor segments have been cast and being finalized before the motors are shipped to KSC for stacking and integration with the core stage. In addition, EM-1 nozzle assemblies are complete. Already at KSC, the forward assemblies for the mission, also Shuttle-era hardware, are in various stages of refurbishment. Stiffeners were added to the forward skirts to address increased buckling loads over Space Shuttle loads. Other changes from the Shuttle-era boosters include moving the rear attach point farther aft to accommodate the core stage structure, new environmentally benign insulation and all-new state-of-art avionics. The boosters will have five avionics boxes, all of which have completed qualification testing at MSFC. The booster avionics will then be tested with the overall vehicle avionics. The aft skirts have been sprayed with a thermal protection system and technicians are currently installing the TVC system.

Fig. 10. Northrop Grumman has nearly completed the five-segment solid rocket boosters for EM-1; motor segments will be shipped to Kennedy Space Center, where they will be stacked to assemble the final boosters.

To support qualification for flight, NASA and SLS have conducted three full-scale static firings of development motors and two full-scale static firings of qualification motors. With the EM-1 five-segment solid rocket boosters so close to completion, Northrop Grumman has begun manufacturing the boosters, including casting the motor segments, for the second flight of SLS and Orion, Exploration Mission 2 (EM-2).

3.4. Upper Stage and Adapters

At the forward section of the rocket, just below the Orion crew vehicle, is the OSA, which holds the secondary payload accommodations. For EM-1, the OSA is complete and was delivered to EGS in February 2018. Made of a lightweight aluminum alloy, the OSA measures 5.4 m in diameter by 1.5 m high. A diaphragm just below the mounting brackets prevents launch gases from entering the Orion spacecraft.

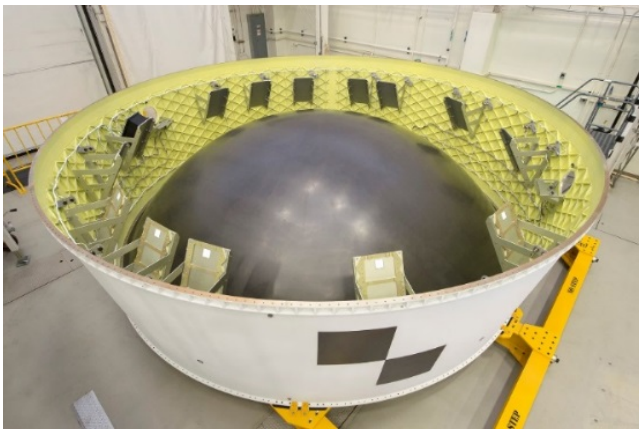

Fig. 11. The finished OSA for EM-1 before it was shipped to EGS; mounting brackets for smallsat COTS dispensers and an avionics box are visible just above the diaphragm.

Sitting just below the OSA, the ICPS, a modified Delta Cryogenic Second Stage manufactured by United Launch Alliance in Decatur, Alabama, USA, supplies in-space propulsion for the Block 1 vehicle. The ICPS will provide the TLI burn to send Orion toward the Moon during the EM-1 mission. After entering its disposal trajectory with the OSA attached, the ICPS will start to release the 13 CubeSats governed by a deployment sequence.

Partially covering the ICPS and providing the diameter adjustment from the 8.4 m core to the 5 m ICPS, the Launch

Fig. 12. The ICPS, which will provide in-space propulsion for the first integrated flight of SLS and Orion, is complete.

Vehicle Stage Adapter (LVSA) is being built by Teledyne Brown Engineering at MSFC in Huntsville, Alabama, USA. The LVSA will provide access to the ICPS during stacking and integration at KSC. The LVSA is nearing completion with instrumentation and cabling installed and thermal protection applied. The LVSA is the largest spaceflight hardware to receive a manually applied thermal protection system at MSFC. The LVSA is scheduled for completion and shipping to the EGS Program at KSC later in 2018.

4. Future Smallsat Payload Accommodations

With funding allocated for a second mobile launcher to be constructed at KSC for SLS's Block 1B configuration, NASA

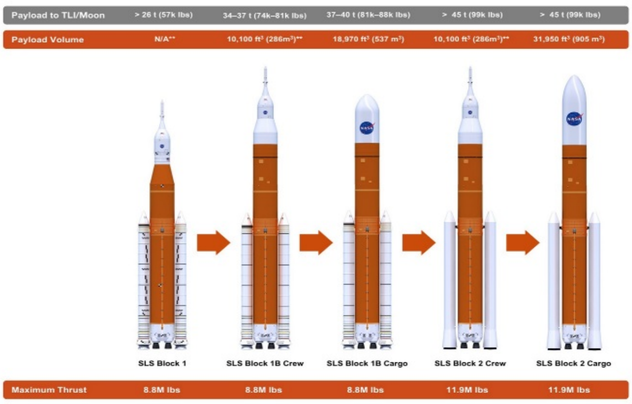

Fig. 13. The SLS family of vehicles that will provide the performance and payload capacity to lift Mars-class payloads.

expects to fly multiple Block 1 flights before transitioning to the more powerful Block 1B variant. Crew and cargo configurations are notionally planned for each block upgrade of the vehicle. The Block 1B vehicle's crewed variant will accommodate co-manifested payloads in a Universal Stage Adapter (USA) that contains as much cargo volume as the Space Shuttle payload bay. For lifting Mars-class payloads, the vehicle will evolve to its most powerful configuration, Block 2. This configuration will lift at least 45 t to TLI. Mission planners will consider opportunities for smallsats on all future flights. Rideshare opportunities as well as propulsive Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapters (ESPA)-class payloads may be accommodated, depending on mission parameters. User demand for propulsive ESPA-class accommodations is currently being evaluated. Larger payloads, in the 200-300 kg class, and constellations of smallsats are within the realm of possibility. Payload developers can expect the Program to provide COTS deployers and other larger COTS payload carrier systems.

4.1. Block 1

Similar to EM-1, the Program is prepared to accommodate secondary payloads in the OSA on future Block 1 flights. The key requirement to "do no harm" to the primary mission will remain in effect, as will phased safety reviews with Program managers. The first crewed flight, EM-2, could potentially provide up to 17 berths for a combination of 6U- and 12U-class smallsats. For that mission, the Program would notionally offer smallsats the opportunity to deploy after clearing the first Van Allen Belt until 10 days after launch, which is past the Moon.

4.2. Block 1B

Depending on capacity available, smallsats in 12U or even larger sizes may be accommodated on SLS Block 1B flights in the 2020s. For Block 1B flights, CubeSats may be integrated onto a payload adapter in a variety of 6U and 12U configurations. The Program would continue to provide mounting hardware integrated into the adapter hardware and an avionics unit to control deployment. Deployment would be available at any point along the upper stage disposal trajectory.

5. Conclusion

NASA's new deep space exploration system, including the SLS vehicle, will revitalize exploration of deep space by enabling the Agency to launch both humans and large payloads of multiple types (primary, co-manifested and secondary). EM-1 is an opportunity for 13 secondary payloads (CubeSats) to explore space and advance science and technologies for the benefit of all humankind. Lessons learned from this first flight will be applied to future flights to enhance and improve exploration opportunities. SLS is well on its way to its first test flight with the Orion spacecraft launching from upgraded facilities at KSC with the Vertical Assembly Building configured to stack the SLS vehicle, the RS-25 engines tested and ready for transportation to KSC and

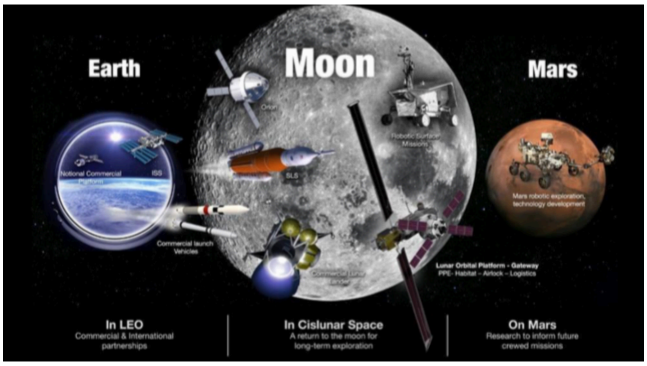

Fig. 14. NASA's long-term plans for deep-space exploration focus on returning astronauts to cislunar space and constructing a lunar Gateway in preparation for exploration of Mars; opportunities for small satellite payloads will likely be a part of these deep-space exploration plans.

the ICPS and OSA hardware elements delivered and at KSC. As the SLS is fielded and matured future flights will capitalize on the substantial mass and volume capability of SLS to enable international and commercial cooperation/exploration to build a new lunar outpost known as Gateway. Along the way, multiple exceptional opportunities for smallsats of various sizes and configurations will likely be available for organizations to affordably reach deep space with groundbreaking science experiments and technology demonstrations.