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Viewpoint

The Moon as an enabling asset for spaceflight

Paul D. Spudis

Lunar and Planetary Institute, United States

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A consequence of the rocket equation is that significant quantities of mass can be lifted into orbit from the bottom of the deepest gravity well in the inner Solar System (Earth's surface) but only at enormous cost. After fifty years of experience and despite technical advances, launch costs continue to make up a major fraction of the cost of space exploration. One-off satellites – launched on expendable vehicles – are still the norm in today's spaceflight paradigm, the same template we have used for the past fifty years. We cannot make what we need in space because we lack both the infrastructure and resources to fabricate our needs at the various places in space where they are needed.

The current lack of strategic direction in the American civil space program is at least partly a consequence of this dilemma. Because we must launch everything we need from the surface of the Earth, spaceflight – especially the human variety – is difficult and costly. This high cost makes justifying human missions into low Earth orbit and beyond difficult and thus, we engage in lengthy debates about appropriate destinations and activities. It is hard to come up with mission goals important enough to merit the spending of significant fractions of national wealth. Debates about mission objectives become mired exercises in scientific mythmaking (e.g., the quest for extraterrestrial life) or appeals to emotion involving "inspiration" or national prestige.

Spaceflight is both useful and important for a wide variety of scientific, economic and national security needs. Satellites make up a critical part of the infrastructure of modern technical civilization. What is needed is the ability to move freely throughout space with a variety of capabilities, where various satellite assets reside, to upgrade, maintain and construct large distributed systems of greater potential and speed. As most satellites reside above low Earth orbit, in cislunar space (i.e., between Earth and Moon), the freedom to move throughout this region would enable us to not only access all of these space assets, but also to travel at will beyond low Earth orbit. However, the problem of the rocket equation remains – we arrive in LEO with empty fuel tanks and to travel farther, we must carry additional fuel and equipment with us. If we could instead provision ourselves once in space, virtually unlimited horizons would beckon.

Fortunately, a source of materials and energy exists nearby that can be tapped to create new space faring capability. Unique among accessible space destinations beyond low Earth orbit, the Moon possesses material and energy resources in usable form to supply a space-based transportation infrastructure, thereby allowing us to establish a permanent presence in space. After nearly a decade of intensive robotic exploration, we now have a detailed understanding of the environment and deposits of the poles of the Moon. Because the Moon's spin axis obliquity is low (1.5° inclination), portions of the terrain near the poles are in either near-permanent sunlight or in permanent darkness. Areas in sunlight can support the generation of electrical power via the emplacement of solar photovoltaic arrays. Infrequent and brief periods of solar eclipse can be bridged through the use of rechargeable fuel cells, which generate electricity by combining hydrogen and oxygen into water. During the periods of solar illumination, solar arrays can then decompose the water back into its component gases, creating a completely reversible process. In addition to its benefits for power generation, illuminated zones near the lunar poles are characterized by constantly grazing incidence of sunlight, which keeps the surface at a nearly uniform temperature of about 220 K (−50 °C). Thus, these polar areas of near-permanent illumination permit extended presence on the Moon, with both constant available power and a benign thermal environment.

Surfaces within the permanently dark areas near the poles of the Moon have extremely low temperatures (25–40 K or −247° to −233 °C) and as a result, act as "cold traps" to collect and retain volatile materials, such as water. Although water is rare on the Moon, its surface is constantly bombarded by water-bearing objects, such as asteroids and comets. This water, vaporized on impact, is mostly lost to space, but it can be preserved if it gets into

E-mail address: Spudis@lpi.usra.edu.

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a cold trap. Recent exploration has shown that these polar cold traps on the Moon contain elevated quantities of volatile substances, including hundreds of millions of tons of water ice.

Water is one of the most useful substances for extended spaceflight. Water supports human life as a consumable, providing drinking water, food reconstitution, and sanitation. Water can be broken into its component gases, hydrogen and oxygen, thus providing air to breathe. Water in quantity is the best shielding material known for high-energy radiation such as cosmic rays, allowing us to venture into deep space beyond the protective shield of the magnetosphere of the Earth. Because it is readily convertible between its compound and component forms in fuel cells, water is a medium of energy storage. Finally, and most significantly, in the form of liquid hydrogen and liquid oxygen, water can be made into the most powerful chemical rocket propellant known. The prospect of making rocket fuel from materials found locally and in abundance on the Moon opens up new vistas of space capability. The quasi-permanent sunlit areas are proximate to cold trap volatile deposits. This relation enables a sustainable presence on the Moon at the poles, where nearly continuous harvesting of water can be conducted. As a consequence of these properties, the Moon becomes an “off-shore” logistics depot for deep space travel.

A significant virtue of the Moon is its closeness to Earth, averaging about 400,000 km. Because of this proximity, it is possible to begin work on the Moon using remote-controlled machines prior to human arrival. With a short, 3-s round trip time lag by radio, teleoperated robots controlled from Earth can begin the assaying and processing of lunar resources. Robotic water harvesting machines can be sent to the Moon as small packages (~1–2 tons) in individual missions and then operated together as an integrated system. This architectural approach makes lunar return affordable and flexible, as the robotic pieces can be delivered to the Moon at a pace and schedule permitted by budgetary considerations.

Robotic systems can begin to extract and store water and also build the infrastructure for a lunar outpost. Individual habitation and logistics modules landed on the Moon autonomously can be emplaced and activated via these robotic teleoperators. The first humans to return to the lunar surface since Apollo would move into a completely functional, “turnkey” outpost, including facilities to refuel their lander vehicle. The crew will live on the Moon in pre-emplaced habitat modules, thus eliminating the need to carry all of their life-support consumables to the lunar surface from the Earth. This architecture allows us to develop a smaller, less costly lander (30 metric ton, “LM-class”) rather than the 50 metric ton lander (“Altair-class”) called for by the Project Constellation architecture.

The new lunar outpost would be intermittently manned by crew (“human-tended) and most of its resource processing work handled by machines, both autonomously for the simple repetitive actions (such as excavation and extraction) and teleoperated (for complex operations, such as fuel loading and machine repair). The lunar outpost will initially be devoted to the production of water, eventually expanding to include the making of building materials (i.e., bulk mass such as aggregate and ceramics for construction, and ultimately metals (e.g., iron, aluminum, titanium) for a variety of structures on the Moon and in space). New industrial technologies such as 3-D printing will allow us to begin fabrication of complex parts and machines from local materials much faster than the historical record for terrestrial industrial development would suggest.

Eventually, lunar water and other products can be exported from the Moon to space. Individual pieces of a space transportation system, including fuel depots, cryogenic processing plants, orbital transfer vehicles, and lunar landers will be permanently based in various locales throughout cislunar space (e.g., L-points, lunar orbit, low Earth orbit). After each journey, these vehicles will be re-fueled and refurbished for ongoing use. Lunar products will supply this transportation system, one that will be capable of accessing all points between Earth and Moon. Such an infrastructure permits us to routinely visit all of the locations of cislunar space where important satellite assets reside, such as geosynchronous orbit.

The advent of such a transportation and logistical system revolutionizes the paradigm of spaceflight. We are no longer limited only to what we can launch from the surface of the Earth. We become mass- and power-unlimited in space, establishing a permanent foothold there. Large-scale, distributed satellite systems can be built and serviced by human and teleoperated robotic machines. Satellites will have unlimited lifetimes as they can be refueled for orbital maintenance and repaired and upgraded when necessary. This new space-based transportation system will revolutionize the paradigm of satellite-based applications in cislunar space, including communications, navigation, national security and scientific observations.

A system that can routinely access cislunar space is also capable of taking humans to the planets. Thus, by returning to the Moon and learning how to extract and use its material and energy resources, we enable long-term human spaceflight. Lunar return is not a diversion from future human missions to the planets – it is an essential part of a long-term strategy for human expansion into the Solar System. If humanity is to have a future in space, we must learn to use what we find there to survive and thrive. The Moon is thus an enabling asset for extended, long-term human presence in space.