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The Moon: Port of Entry to Cislunar Space

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If God wanted man to become a space-faring species,
He would have given man a Moon. — Krafft Ehricke[1]

One can imagine many possible missions and destinations for America's civil space program. Voyages to the planets, large scientific instruments at orbital libration points, and continued use of the International Space Station (ISS) are all possible missions of both machines and people from many countries in the coming decades. With the imminent completion of the ISS and retirement of the space shuttle, a national discussion has emerged as to both the purpose and rationale for human spaceflight.

The Vision for Space Exploration (VSE) outlined by President George W. Bush in 2004[2] and endorsed by Congress in 2005[3] and 2008[4] (under different parties) called for human missions beyond low Earth orbit (LEO), including a return to the Moon. The inclusion of the Moon has drawn comment from the space community, many of whom think that since the Apollo program ended over three decades ago, it was included as a way to regain valuable experience. In fact, the Moon is the critical element of the VSE. It is where we will learn how to use what we find in space to create new spacefaring capability.

Why the Moon?

The Moon has a major advantage over other potential destinations beyond LEO as it is both close and easily accessible. Only a 3-day trip from Earth, the Moon is close enough for existing space systems to reach. Additionally, it is only a 3-light-second round trip between Earth and Moon, which allows robotic missions on the lunar surface to be controlled remotely from the Earth in near real time. The Moon's low gravity permits landing and operations with a minimal expenditure of energy.

The Moon is a scientific laboratory of unique character. Its location near Earth ensures that it records the geological history of this part of the solar system. Such history includes the impact of solid objects and the solar wind and their possible changes with time. It holds a historical record of cosmic radiation, including nearby supernovae. The Moon's timeless surface preserves a record of ancient events, and whatever is preserved on the lunar surface must have also affected the Earth. This record is long gone from our dynamic terrestrial surface but remains preserved on the static, ancient lunar surface.

The Moon has the material and energy resources needed to support human presence and to begin building a long-lasting transportation infrastructure. Its surface is covered by a very fine-grained soil that is useful as radiation shielding and building material.[5] Oxygen extracted from lunar materials can support life and be used for rocket propellant. Light elements, such as hydrogen, helium, and nitrogen, are present in the lunar soil in low concentrations, but in enough quantity to permit their extraction and use. More importantly, we now find that significant amounts of hydrogen are present in soils at high latitudes and that the polar areas may contain water ice in permanently dark areas. Because the spin axis of the Moon is nearly perpendicular to its orbit around the Sun, some areas at the poles are in near-permanent sunlight. This is a unique asset: areas in constant sunlight for power generation are proximate to shadowed terrain enriched in the light elements, such as hydrogen. Another asset unique to the Moon is its far side, the only place in our solar system permanently shielded from Earth's radio noise. Here we can scan the sky to observe the universe in entirely new areas of the spectrum.

The Moon is the first, but not the last, destination in the VSE. It is not only an important destination in its own right, but also an enabling asset. The objective of this program is to go to the Moon to learn how to use off-planet resources to create new capability and to make future space flight easier and cheaper.[6] Rocket propellant made on the Moon permits routine access to cislunar space by both people and machines, and is vital to the servicing and protection of national strategic assets and for the repair and refurbishing of commercial satellites. The United States cannot afford to forfeit its lead in the access of cislunar space. There are serious national security and economic ramifications if our leaders fail to recognize the importance of the Moon to our future in space and here on Earth.

Spaceflight: The Current Template

Fifty years of space travel have been possible because we accepted the iron rules of spaceflight that are dictated by the rocket equation.[7] In brief, this requires a significant expenditure of energy to get something out of the deep gravity well in which the Earth resides. As it is very expensive to escape this gravity field, the things we launch into space are made as small and low in mass as possible. As long as this mode of operation prevails, we are mass- and power-limited in space and therefore, capability-limited. These limitations greatly restrict what we can do in space.

The prevailing rules of spaceflight have led to the development of a template of operations for satellites and other space assets. For a given mission, a specialized, usually custom, spacecraft is designed. The spacecraft is built to exceedingly fine standards, with numerous environmental tests and retests. It is launched on an expendable vehicle into a specially designed orbit and in most cases is unreachable by other spacecraft. If all goes well, it is operated for as long as possible and ultimately abandoned. The entire process is then repeated. Sometimes, by incorporating the results from previous missions, the design is improved.

Because each satellite is eventually thrown away, space operations are expensive and difficult. If it were possible, these assets would benefit greatly from servicing, maintenance, and expansion. A system that routinely accesses orbiting satellites with servicing robots and people would fundamentally change our approach to spaceflight. The difficulty in developing this capability is that the machines and propellant we would need to do this must also be lifted up from the deep gravity well, again at great cost and difficulty. The greatest mass of this system is rocket propellant.

If we develop a source of rocket propellant in space (so that we do not have to lift it up from Earth's surface), a new type of operational template might be possible. Instead of one-off designs and throwaway assets, we would think about long-term, extensible, and maintainable modular systems. The availability of a source of rocket propellant in LEO would completely change the way engineers design spacecraft and the way companies and the government think about investing in space assets. It would serve to dramatically reduce the cost of infrastructure in space to both government and the private sector, thus spurring economic investment (and profit).

Cislunar Space: Where All Our Assets Reside

The various altitudes and levels of orbit around the Earth[8] create very different environments and capabilities and hence are utilized by many different types of satellites designed to take advantage of the opportunities they offer. The closest zone is LEO, a space lying roughly within 2,000 kilometers (km) from the Earth, with most satellites operating around 200 to 300 km. It is within this zone most human and robotic space activity occurs. All satellites must at least pass through this zone before arriving at their final destinations.

LEO has many advantages for a variety of missions, including being where orbits are closest and easiest to get to. It is largely below the Van Allen radiation belts, so spacecraft and instruments are protected from hard radiation. Robotic satellites carry out a variety of scientific missions including orbital remote sensing of Earth and its atmosphere. Extended human missions are undertaken in LEO, both on temporary orbital spacecraft such as the shuttle and permanent facilities such as the ISS. Orbital periods are low (on the order of 90 minutes) and repeat passes occur at least twice a day over the same area from inclined orbits (and on every pass from an equatorial orbit).

Medium Earth orbits (MEO) range from 2,000 km up to about 35,000 km altitude. Orbital periods become much longer, which is useful for space applications that require long visibility times, such as global positioning systems (GPS). Typically, such applications are achieved using constellations of multiple satellites, such that two or more assets can work in tandem to achieve the desired result. MEO comprises the Van Allen radiation belts and thus is a difficult environment in which to maintain satellite life.

Highly elliptical orbits (HEO) are very elongated (thousands of kilometers at apogee, the high point of such an orbit) and have very long orbital periods. Because of their very long dwell times at apogee, these orbits are used in some national security missions, as they can "hover" over specific areas for long periods of time. Satellite radio also uses this zone of cislunar space.

Geosynchronous orbits occur around 35,000 km altitude; their periods coincide with the rotation period of the Earth, and thus the satellites appear twice a day over the same spot on the Earth's surface. A perfectly equatorial orbit at 35,786 km is a geostationary orbit (GEO), in which a satellite appears to be stationary in the sky. These orbits are widely used by all nations for a variety of communications purposes and for global weather observation and monitoring. GEO is one of the most valuable places in Earth orbit.

Beyond GEO are the Earth-Moon libration points (also called Lagrange points)[9]; L1 through L3 are in line with the Earth-Moon baseline, while L4 and L5 trail and lead the Moon in its orbit around the Earth. Except for the occasional scientific mission, such as a solar wind monitor, the L-points are not used by spacefaring nations at present. These points are of great value for transportation nodes and logistics depots. Because they are gravitational equipotential points (or weak stability boundaries),[10] all points in cislunar space can be reached from the L-points with minimal changes in velocity. After the L-points, the Moon is the next dominant feature in cislunar space. Both lunar orbit and the lunar surface are possible destinations; both are easily accessed using minimal additional energy from GEO or the Lagrange points.

All zones of cislunar space have practical and theoretical uses.[11] All are accessible with existing systems, but only once. To continually revisit a given space asset, we must build a duplicate of the system that originally got us there. For example, if a communications satellite in GEO stops working, the only alternative is to design, build, and launch a completely new satellite. There is no way to send either servicing crews or machines to repair or upgrade the balky equipment. In short, if the fundamental premise of being a spacefaring nation is the ability to routinely conduct missions anywhere in space for a variety of purposes, we are actually quite far from that capability.

The Value of the Moon

Rock and soil samples returned by the Apollo missions taught us the fundamental chemical makeup of the Moon. It is a very dry, chemically reduced object, rich in refractory elements but poor in volatile elements. Its composition is rather ordinary, made up of common rock-forming minerals such as plagioclase (an aluminum-calcium silicate), pyroxene (a magnesium-iron silicate), and ilmenite (an iron-titanium oxide). The Moon is approximately 45 percent oxygen by weight,[12] but this oxygen is tightly bound to metals in the surface rocks. Light elements, including hydrogen and carbon, are present in small amounts—in a typical soil, hydrogen makes up between 50 and 90 parts per million by weight, with similar quantities of carbon and nitrogen. Soils richer in titanium appear to be also richer in hydrogen, thus allowing us to infer the extent of hydrogen abundance from the titanium concentration mapped from orbit.

Lunar materials offer many possible uses. Because radiation is a serious problem for human spaceflight beyond LEO, the simple expedient of covering surface habitats with soil can protect future inhabitants from both galactic cosmic rays and even solar flares. Lunar soil (regolith) can be sintered by microwave into very strong building materials, including bricks and anhydrous glasses that have strengths many times that of steel.[13] When we return to the Moon, we will have no shortage of useful building materials.

Because of its abundance on the Moon, oxygen is likely to be an important early product. The production of oxygen from lunar materials simply involves breaking the very tight chemical bonds between oxygen and various metals in minerals.[14] Many different techniques to accomplish this task have been developed; all are based on common industrial processes easily adapted to use on the Moon. Besides human life support, the most important use of oxygen in its liquid form is rocket fuel oxidizer. Coupled with the extraction of solar wind hydrogen from the soil, this processing can make rocket fuel the most important commodity of a new lunar economy.[15]

The Moon has no atmosphere or global magnetic field, so solar wind (the tenuous stream of gases emitted by the Sun, mostly hydrogen) is directly implanted onto surface dust grains. Although solar wind hydrogen is present in very small quantities over most of the Moon, it too can be extracted from the soil. Soil heated to about 700°C releases more than 90 percent of its adsorbed solar gases.[16] Such heat can be obtained from collecting and concentrating solar energy using focusing mirrors. Collected by robotic processing rovers, solar wind hydrogen can be harvested from virtually any location on the Moon. The recent discovery that hydrated minerals are abundant at higher latitudes suggests that water is being created constantly at the lunar surface.[17] Some of this water migrates to the poles where it may be concentrated in abundance, thereby making its potential collection and use much easier.

The Department of Defense–National Aeronautics and Space Administration (NASA) Clementine mission in 1994 made global maps of the mineral and elemental content of the Moon. It mapped the shape and topography of its surface with a laser altimeter and gave us our first good look at the intriguing and unique polar regions.[18] Clementine did not carry instruments specifically designed to look for water but an ingenious improvisation used the spacecraft communications antenna to beam radio waves into the polar regions; the resulting radio echoes, which were observed using antennas on Earth, indicate that material with reflection characteristics similar to ice is found in the permanently dark areas near the south pole.[19] This discovery was supported subsequently by the discovery of large amounts of hydrogen near both poles[20] by a neutron spectrometer flown on NASA's Lunar Prospector spacecraft[21] in 1998.

Water is added to the Moon over geological time by the impact of comets and water-bearing asteroids. Because the Moon's axis of rotation is nearly perpendicular to the plane of the ecliptic (the plane in which Earth and Moon orbit the Sun), the Sun is always near the horizon at the poles. If you are in a hole, you never see the Sun, and if you are on a peak, you always see it—the Sun goes around, not up and down. Depressions near the poles never receive sunlight; these dark areas are very cold—only a few degrees above absolute zero.[22] Any water that gets into these polar cold traps cannot get out, and over time, significant quantities can accumulate. Our current best estimate is that over 10 billion cubic meters of water exist at the poles,[23] an amount roughly equal to the volume of Utah's Great Salt Lake. Although hydrogen and oxygen can be extracted directly from the soil as described above, such processing is difficult and energy-intensive. Polar water has the advantage of being in an already concentrated form, greatly simplifying scenarios for lunar return and habitation. Broken down into hydrogen and oxygen, water is a vital substance both for human life support and rocket propellant.

The poles of the Moon are useful from yet another vital resource perspective: the areas of permanent darkness are proximate to areas of near-permanent sunlight. We have identified several areas near both the north and south poles that offer near-constant illumination by the Sun.[24] Moreover, such areas are in darkness for short periods, interrupting longer periods of illumination. An outpost or establishment in these areas will have the advantage of being in sunlight for the generation of electrical power (via solar cells) and in a benign thermal environment (because the sun is always at grazing incidence, the surface temperature remains a near-constant -50° ± 10°C);[25] such a location never experiences the temperature extremes found on the equator (from 100° to –150°C) and thus, thermal control is much easier, making the poles of the Moon inviting "oases" in near-Earth space.

Besides its material and energy resources, the Moon is an operational laboratory where we can experiment with and learn how to conduct planetary surface exploration, utilization, and habitation. The Moon is a world, alien yet familiar, that allows us to learn the skills needed to make other worlds part of humanity's universe. Those skills can be summarized by the words "arrive, survive, and thrive." We need to develop a system that allows access to the lunar surface on a routine basis. Thus, we require long-lived reusable subsystems and equipment that can take advantage of products made from lunar resources. To survive on the Moon, we must protect humans and equipment from the harsh surface environment and make consumables. Water production protects habitats and supports people with drinking water and breathable oxygen. But for permanent human presence on the Moon, we must not only survive, but also thrive. This means that we must make "a profit": some product that we make on the Moon must exceed the value of the investment in building surface infrastructure. In the near term, such a product is likely to be lunar water, the currency of cislunar space. Water exported from the Moon can be used to make rocket propellant to fuel a transportation infrastructure and thereby lower the costs of spaceflight.

Lunar Return: Incremental Steps

Although we possess enough information now to plan a lunar return, we should conduct new robotic missions to reduce programmatic risk and to generate program milestones. The Lunar Reconnaissance Orbiter (LRO)[26] is now mapping the Moon in detail—collecting information on the physical nature of the surface, especially the exotic and poorly understood environment of the polar regions. LRO is mapping the polar deposits of the Moon using imaging radar to "see" into the dark regions. Such mapping will establish the details of water ice locations as well as its thickness, purity, and physical state. The next step is to land small robotic probes to conduct chemical analyses of the polar deposits. Although we expect water ice to dominate the deposit, comets are made of many different substances, including methane, ammonia, and organic molecules, all preserved in the polar regions and all potentially useful resources. We need to inventory these substances and determine their chemical and isotopic properties as well as their physical nature and local environment. Just as robotic missions such as Ranger and Surveyor[27] paved the way for Apollo, a new set of robotic precursors will make subsequent human missions safer and more productive.

As soon as robotic orbiters and landers have documented the nature of the deposits, focused exploration and research should be undertaken to develop the machinery needed to harvest and process the resources of the Moon. We must understand the physical nature of the polar deposits and how we might extract water from its (currently unknown) native state. This could mean excavating and moving dirt and/or developing schemes that remove the water in place. A variety of mining and extraction processes can be experimented with using robotic missions, thus paving the way to industrial-scale activities and commercialization of the production of hydrogen and oxygen from lunar materials.

Forty years ago, America built the mighty Saturn V to launch men and machines to the Moon in one fell swoop. This technical approach was so successful that it has dominated the thinking on lunar return for decades. One feature of nearly all architectures of the past 20 years is the initial requirement to build or rebuild the heavy lift launch capability of the Saturn V or its equivalent. However, parts of the Saturn V were literally handmade,[28] making it a very expensive spacecraft. Development of any new launch vehicle is an enormously expensive proposition. What is needed is an architecture that permits lunar return with the least amount of new vehicle development possible (and hence, the lowest possible cost.) Such a plan will allow concentration of effort and energy on the most important aspects of the mission: learning how to use the Moon's resources to support space flight beyond low Earth orbit.[29]

To deliver the pieces of the lunar spacecraft to Earth orbit—lander, habitat, and transfer stage—the architecture should use existing launch assets, including shuttle-derived components augmented by existing expendable boosters. Assembled into a package in space, these items are then transferred to the Moon-Earth L1. The L1 point orbits the Earth with the Moon such that it appears "motionless" in space to both bodies. Because there is no requirement for quick transit, cargo and unmanned mission elements can take advantage of innovative technologies such as solar electric propulsion and the weak stability boundaries between Earth, Sun, and Moon to make long, spiraling trips out to L1, thus requiring less propellant mass launched from Earth.[30] These unmanned cargo spacecraft can take several months to get to their destinations. The habitat module can be landed on the Moon by remote control and activated to await the arrival of its occupants from Earth. Previously landed robotic rovers and robots become part of the surface infrastructure and can be used telerobotically to prepare and emplace outpost elements.

The human crew is launched separately in the crew exploration vehicle and uses a chemical stage and a quick transfer trajectory to reach the L1 depot in a few days. There, the crew can transfer to the lunar lander, descend to the surface, and occupy the pre-emplaced habitat. Because the outpost elements are already on the Moon, the lunar lander does not have to be the 50-metric-ton behemoth called for by the Exploration

Systems Architecture Study,[31] but rather a much smaller, reusable version—its only job is to transfer the crew from L1 to the lunar surface.

The preferred site for a lunar outpost is at one of the almost permanently sunlit areas near a pole of the Moon. The south pole is attractive from the perspective of both science and operations, but final selection should await complete surveys of the poles, so as to locate the outpost as close as possible to the highest grade resources. The strategy on the Moon is to learn how to mine its resources and build up surface infrastructure to permit ever-increasing scales of operation. Each mission brings new components to the surface, and the size and capability of the outpost grows over time.

Resource utilization on the Moon will expand with time. Initially, demonstration production levels of a few kilograms of product (water, oxygen) will document the difficulty of mining and processing. After we determine the optimum techniques, our initial production goals are to make consumables (water for drinking, air, and shielding, in that order); this requires production levels of hundreds of kilograms. Once this is well established, we can begin to make rocket propellant. Initial propellant production at the metric ton level can support extended exploration around the lunar outpost and perhaps ballistic flights to other locations on the Moon. A major breakpoint will come with the production of tens to hundreds of tons of propellant; at such a level, we can export our surplus propellant to depots in cislunar space, making it available for commercial sale to many different users. It is the ultimate realization of this act that creates a cislunar economy and demonstrates a positive return on investment.[32]

In addition to its technical advantages, this architecture offers important programmatic benefits. It does not require the development of a new heavy lift launcher. Costs in space launch are almost completely dominated by the costs of people and infrastructure. Creating a new launch system requires new infrastructure, new people, and new training. Such costs make up significant fractions of the total program. By using existing systems,[33] we concentrate our resources on new equipment and technology, all focused toward the goal of finding, characterizing, processing, and using lunar resources as soon as possible. The use of the L1 point as a staging depot allows us to depart at any time for both the Earth and Moon; the energy required to go nearly anywhere beyond this point is very low. The use of existing, low-thrust propulsion technology (that is, solar-electric) for cargo elements permits us to use time as an asset, not an enemy. We will acquire new technical innovation as a byproduct of the objective, not as a critical requirement of the architecture.

A New Template for Spacefaring

By mining the Moon for water, we establish a robust transportation infrastructure capable of delivering people and machines throughout cislunar space. Make no mistake: learning to use the resources of the Moon or any other planetary object will be a challenging technical task. We must learn to use machines in remote, hostile environments while working under difficult conditions to extract ore bodies of small concentration. The unique polar environment, with its zones of near-permanent illumination and permanent darkness, provides its own challenges. But for humanity to live and work in space, we must learn to use the material and energy resources available off-planet. We are fortunate that the Moon offers us a nearby "safe" laboratory where we can take our first steps toward using space resources. Initial blunders in operational approach or feedstock processing are better practiced at a location 3 days from the Earth than one many months away.

A return to the Moon to learn how to use its resources is scalable in both level of effort and the types of commodities to be produced. We begin by using the resources that are easiest to extract. Thus, the logical first product is water derived from the polar deposits. Water can be produced there regardless of the nature of the polar volatiles; ice of cometary origin is easily collected and purified. If the polar materials are composed instead of molecular hydrogen, this substance can be combined with oxygen extracted through a variety of processes from rocks and soil to make water. Water is easily stored and will be used as a life-sustaining substance or retained in a separated, cryogenic state for use as rocket propellant.

The world relies on a variety of satellites in cislunar space—weather satellites, GPS, communications systems, and a wide variety of reconnaissance platforms. Commercial spacecraft makes up a multi-billion-dollar market, providing telephone, Internet, radio, and video services. America has invested billions in space hardware. Yet at the moment, we have no infrastructure to service, repair, refurbish, or protect any of these spacecraft. They are vulnerable to severe damage or permanent loss by accident or intentional action. If we lose a satellite, it must be replaced. From redesign though fabrication and launch, such replacement takes years and involves extraordinary investment in the design and fabrication to make them as reliable as possible.

We cannot access these spacecraft because it is not feasible to maintain a human-tended servicing capability in Earth orbit; at thousands of dollars per pound, the costs of launching orbital transfer vehicles and propellant are excessive. Creating the ability to refuel in orbit by using propellant made from lunar materials will revolutionize the way nations view and use space. Satellites will be repaired rather than abandoned. Assets can be protected rather than written off. Very large satellite complexes can be built and serviced over long periods, creating new capabilities and expanding bandwidth (a critical commodity of modern society) for a wide variety of purposes. And along the way, there will be new opportunities and discoveries. We will become a true spacefaring species.

A return to the Moon with the purpose of learning to extract and use its resources creates a new paradigm for space operations. Space becomes a realm in our economic sphere, not an exotic environment for arcane studies. Such a mission ties the American space program to its original roots, making us more secure and more prosperous. It also enables new and broader opportunities for science and exploration. A transportation infrastructure that can routinely access various points of cislunar space can take humanity to the planets. We will learn to use what we find in space to create new spacefaring capabilities. A cislunar transportation system, fueled by lunar propellant, will be the transcontinental railroad of the new millennium.[34]

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