Lunar exploration: the next step

Iridium gets real

X-33 and RLV take parallel paths
Lunar exploration:

A small mission to the Moon would add to exciting recent discoveries and could revolutionize our understanding of Earth's nearest neighbor.

The past few years have shown that our understanding of the Moon is incomplete. New knowledge about the nature of the lunar poles suggests that living on and using the Moon might be easier than we thought. This knowledge has implications for humanity's future on both the Earth and the Moon. Although the new information is exciting, it raises more questions than it answers. Its incompleteness challenges us to find answers to the remaining unknowns. The time may now be right to take the initiative and seize the opportunities provided by the Moon to move outward into the solar system.

New insight into lunar poles

With the successful flights of the DOD's Clementine mission in 1994 and NASA's Lunar Prospector mission in 1998, we have learned more about the polar regions of our nearest planetary neighbor. These missions represent the first steps in the Space Exploration Initiative (SEI) outlined by the Synthesis Group in 1991. Clementine specifically supported previous space policy directives encouraging DOD and the Dept. of Energy to contribute to SEI through high-leverage technology demonstration.

We knew the use of in situ resources, particularly water, would have a significant impact on the economic feasibility of SEI, and that lunar resources would therefore have to be assayed. These missions have provided new insights into the distribution of lunar resources.

The poles of the Moon are a unique environment. Because the Moon's spin axis is nearly perpendicular to the ecliptic plane (tilted only 1.6° from the vertical), the Sun appears close to the horizon at both poles as the Moon slowly rotates over the course of its 708-hr day. If the Moon were a perfectly smooth sphere, the Sun would dip just below and rise just above the horizon over the course of a lunar day.

However, the Moon is not smooth. The extremely rough terrain of the lunar polar highlands creates zones of shadow and light. For the dark areas, these zones may have been in darkness for as long as the current orientation of the lunar spin axis, presently thought to be several billion years. These dark zones are thus extremely cold, as the only heat they receive is from the lu-
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narrow interior (a few milliwatts per square meter) and the cosmic background of deep space (3 K, or about −270 °C). The lunar cold traps are estimated to have temperatures on the order of 50 K (about −223 °C). In such a cold environment, any volatile substance would be stable for essentially geological time scales—billions of years.

The Moon is also extremely dry. Studies of lunar samples returned by the Apollo missions show that its rocks were created in an environment virtually devoid of water. Yet we know that the Moon's craters have been produced over the last 4 billion years by the impact of asteroids and comets, and that both objects contain water. In fact, water makes up as much as 90% of the mass of cometary nuclei. Because of the extreme thermal environment over most of the face of the Moon (daytime temperatures near its equator range from 100 °C during lunar noon to less than −150 °C at midnight), any water added to the Moon by impacting comets is quickly disassociated and driven off into space.

But water that manages to get into the cold traps at the poles has no way to escape, lacking both the thermal energy to leave the traps and a mechanism for being driven off the Moon. The accumulation of this water would be extremely slow, with literally just a few molecules per year being added, but it would be relentless. Over billions of years, a considerable amount of water would build up. Thus, despite the Apollo sample evidence for a dry Moon, some scientists believed that a search for
water ice in the dark areas near the lunar poles might prove fruitful.

Our first chance to address this important question came during the Clementine mission in 1994. Clementine was in a polar orbit but did not carry instruments designed to search specifically for polar water. However, a clever improvisation allowed us to use the spacecraft radio transmitter as a “flashlight” shining into the dark areas near the poles. Our analysis suggested the presence of material with radar-scattering properties similar to those of ice, and we interpreted the results as indicating significant amounts of water at the south pole of the Moon, where we observed the most shadowed area.

Although this interpretation was questioned, recent data from the neutron spectrometer carried by the Lunar Prospector spacecraft confirm the presence of significant amounts of water ice at both lunar poles. Clementine failed to detect evidence of ice at the north pole, because the largest areas of north polar Sun shadow also correspond to areas of radar shadow and were not well observed. The total amount of lunar water is estimated to be on the order of 10 billion tonnes (or 10 km$^3$), roughly equivalent to the volume of Utah’s Great Salt Lake (without the salt).

**Water as fuel**

This discovery is significant in several respects. Water is a versatile resource and can be repackaged as hydrogen and oxygen to serve as propellant, fuel cell reagents, chemical feedstocks, and gases to support human life. Thus a large deposit of water makes the Moon much easier to inhabit. Data from Clementine and Lunar Prospector suggest that the equivalent of tens of millions of Space Shuttle cargo bay payloads of water exist in the polar cold traps. Useful trace volatiles such as xenon (for electric propulsion), halogens (high-energy fuels), and ammonia are also likely to be present in significant amounts.

The ability to refuel transportation systems in Earth-Moon space and to manufacture useful products will significantly improve the economics of a permanent base on the Moon. The International Space Station still requires every gram of its mass to be transported from Earth, at significant launch costs. While lunar water is a limited resource, it will be supplemented by more difficult mining of virtually unlimited solar wind gases once a mature base exists.

Scientifically, the water at the poles retains a record of the volatiles emplaced on the Moon over the past few billion years. As this water is derived from primitive, unevolved comets, lunar polar water and its associated volatiles tell us about the earliest stages of solar system evolution. Study of this ice can yield new insight into the conditions of the solar system’s formation as well as its volatile history and evolution.

**A user-friendlier environment**

The lunar poles have another value. In addition to the general problems of space operations—the vacuum and hard radiation environment—the Moon’s surface near the equator presents an extreme thermal environment, with a 250 °C temperature swing over the course of a lunar day (28 Earth days). Moreover, the two-week duration of the lunar night imposes significant constraints on lunar surface operations, requiring the use of nuclear reactors for power generation. However, many of these harsh factors are mitigated at the poles. Peaks in the polar region receive sunlight for significant fractions of the lunar day. Our analysis of an area close to the south pole and near the rim of the crater Shackleton shows it is illuminated more than 70% of the lunar day during southern winter (this fraction would be greater during the summer season).

These illuminated areas have a relatively benign thermal environment (∼50 ±10 °C), experiencing neither the direct radiation of an overhead Sun (and its accompanying passive thermal radiation from the surrounding areas of the surface) nor the bone-chilling cold of lunar midnight. The long shadows make for safer landings. Near-constant solar illumination provides a direct source of uninterrupted energy, so an installation could derive its power nearly
exclusively from solar sources. Energy storage during the dark periods, lasting from a few hours to as much as a day, could be accomplished efficiently by using the lunar-derived water as reagents for regenerative fuel cells. In addition, several sites could alternate power production over the course of a lunar day.

Studies of lunar surface operations show that one of the biggest problems on the Moon is keeping cool. The Apollo missions used open-cycle water evaporation systems that limited surface stay times. If we must rely on passive radiators, the mass of the thermal control system grows rapidly. Efficient gas/liquid heat transfer with ammonia or other lunar-derived gases, which can condense in the nearby cold traps, will enable thermodynamically efficient, energy-extensive activities, such as the use of solar thermal power for process heat and power generation. Water also makes excellent radiation shielding that can be pumped into mass- and volume-efficient double-walled inflatable habitats.

**Advantages of a lunar base**

Studies of lunar bases carried out in past decades, including those conducted by the Synthesis Group, have identified astronomy as a major scientific objective of a lunar base. From the poles, the radio-quiet far side of the Moon is only a short distance “over the hill.” The near-permanent night and cold of these areas could make for unique infrared and optical astronomy. The vast, seismically stable lunar surface will also allow the construction of interferometers of baselines of tens of kilometers, with solid optical benches, an array allowing a new and unique view of the universe.

The Synthesis Group advocated the use of the Moon as a test bed for safer development of the tools and skills needed for further exploration closer to home, and as a source of resources to use in space and eventually on Earth. For example, a lunar base would allow the safe development and testing of nuclear power for space applications well outside of the terrestrial biosphere. Crews returning with samples from Mars or robotic spacecraft returning samples from comets or the Jovian satellite Europa might also find the Moon an effective quarantine zone for protecting the terrestrial biosphere from possible infection.

For the first people to live “off-planet,” the one-sixth gravity environment of the Moon allows a more Earth-like, less artificial lifestyle. Instead of spending hours on a treadmill to keep in shape in microgravity, lunar crews might wear weighted clothing. Near-constant solar illumination will be easier to modulate into an Earth-like day/night cycle for plant growth. Artificial illumination may be required for only a few days per month. The presence of abundant water will also enable amenities such as flush toilets and frequent hot showers.

**Finishing the map**

These potential applications and the exciting new discoveries about the poles of the Moon invite a serious and detailed investigation of the polar environment. Studies using existing Clementine and Lunar Prospector data are currently under way. However, finding the definitive answers to many questions about the polar regions will be possible only with new exploration. We have tentatively identified areas that appear to be illuminated for more than 50% of the lunar day. However, Clementine orbited the Moon for only 71 days and could not follow the changing illumination conditions over a full seasonal cycle (although the axis tilt of the Moon is minor, it could be significant). While Clementine made the first global map of lunar topography, orbital constraints prevented the acquisition of ranging data from latitudes greater than 70°.

Although we have inferred the topography of these areas from stereo images made by Clementine, such mapping needs to be checked. A detailed characterization of the polar environment requires that we carefully identify illuminated and dark areas, their temporal variation, and the thermal conditions within them.

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This knowledge can be obtained by imaging the poles over the course of a year, measuring the topography of the polar regions by ranging from the spacecraft, and using thermal infrared to determine the temperature of light and dark regions around the pole. Such data can be used to make maps showing environmental conditions and their variation around both poles. Images will directly show illumination conditions, allowing us to determine the fractional time illuminated and document times and duration of local shadow intervals.

Ranging can be accomplished either by radio or laser; use of the Clementine LIDAR instrument is feasible if the spacecraft is placed in a circular orbit closer than 500 km to each pole. Thermal conditions are easily obtained by using a long-wave infrared sensor. A LIDAR could also be combined with a high-resolution imager and could serve as a "flash camera" to image the permanent shadowed areas, allowing detailed knowledge to be collected as to the surface conditions, morphology, and potential hazards.

Given that ice occurs near the poles of the Moon, we still have limited understanding of its purity, composition, and physical setting. Some issues, such as the chemical and isotopic makeup of the ice, cannot be addressed by a simple orbital mission. However, a radar imaging experiment could provide significant amounts of information on the location, purity, and extent of lunar ice. Such a radar instrument (which has never been flown to the Moon) could map the interior of the permanently dark zones, determine the presence of ice by backscatter properties, and assay its relative purity (the amount of rock and soil mixed with ice) by measuring the strength of the echo and its polarization. This type of instrument can be straightforwardly developed from the advanced lightweight RF technology developed by Clementine. When combined with information from imaging and ranging, the resulting data will give us a three-dimensional model of the polar regions, the dark and light areas, and the locations and characteristics of the enclosed ice deposits.

These measurements would be critical to planning the next step, that of targeting robotic landers to the most promising locations and sampling the ice and polar environment directly. This surface phase could be accomplished on the same mission, after the necessary orbital data are gathered, or on separate missions as dictated by cost, schedule, and organizational participation.

The missions required prior to the next phase of lunar exploration will have to be conducted in ways not practiced since Apollo, as their primary objectives are utilitarian, not purely scientific, and they must be evaluated by this "economic" criterion. They are pathfinders for human exploration. They must also be cost-effective.

Clementine ($80 million and two years) and Lunar Prospector ($70 million and three years) have successfully demonstrated the viability of this "prospecting" approach. Such efforts can be conducted quickly and cheaply, without any sacrifice of scientific or technological excellence. A new orbital mission designed along these lines could accomplish the goals just articulated quickly and inexpensively.

Stepping stone
Terrestrial life has always inhabited those niches that could support it. One key ingredient in the support of life is water. Throughout human history, we have always camped near the river, lake, or well. Humans will move outside Earth and colonize space only if they can survive there and do useful work that justifies the effort. We have learned that the Moon, our nearest planetary neighbor, can sustain life more easily than we had previously thought. This knowledge resulted from the successful implementation of "faster-cheaper-better" practices, the use of advanced, lightweight technology developed for national security missions, and a utilitarian "economic geology" approach to unmanned space exploration. Continuing this practice will pave the way for the exploration and utilization of the Moon, both for its own sake and as a stepping stone to the more challenging journeys beyond.