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Small Spacecraft Mission Concepts to Achieve Lunar Science and Exploration Goals

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ABSTRACT

NASA's Vision for Space Exploration calls for a return to the Moon with both robotic spacecraft and human explorers in the coming decades. Both scientific and exploration-related goals can be achieved using a small spacecraft platform with relatively low cost and rapid development time. We report on mission concepts within five investigation themes and provide traceability to proposed instrumentation and measurement objectives. Specific

themes addressed here include 1) Water, 2) Radiation Shielding, 3) Biologic Effects of the Lunar Environment, 4) Dust and Regolith Characterization, and 5) Enabling Lunar Astrophysics.

THEME 1: WATER

Understanding the nature of any water ice on the Moon is critical for in situ resource utilization for human exploration and is also of intrinsic scientific merit. The presence or absence of frozen water ice in the permanently shadowed regions of the Moon is still a controversial – and unresolved – issue. Currently available data are inconclusive. To place the controversy in context, we present a summary of the published literature on the topic below.

Background

Nozette et al. (1996) report on the results of the Clementine Bistatic Radar Experiment[1]. Results are cited which support an observed enhancement localized to the permanently shadowed regions of the lunar south pole. No enhancement is seen in permanently shadowed regions of the north pole of in sunlit areas. These observations are interpreted as evidence for the presence of ice in the permanently shadowed regions of the south pole[1].

Nozette et al. (2001) report enhanced levels of hydrogen detected by Lunar Prospector within regions of permanent shadow at the lunar south pole, especially at Shackleton Crater[2]. These same areas also reportedly correlate with the Clementine bistatic radar data which is also interpreted as being indicative of ice. Arecibo data is also reported to correlate with "anomalous" high values observed by Arecibo on the lower, sun-shadowed wall of Shackleton Crater. Nozette et al. (2001) estimate from Arecibo and Clementine data that 100 square km of ice may be present on the Earth-facing wall of Shackleton Crater[2]. None of the data is definitive but taken together it is plausible that ice occurs in the cold traps on the Moon[2].

Feldman et al. (1998) report the detection of enhanced hydrogen levels at the lunar poles[3]. Observations are consistent with water ice covered by as much as 40 cm of desiccated regolith within permanently shadowed craters near both poles. However, this model is not unique. Similar results could results from lower water ice abundances in a buried deposit, different surface area and surface distribution of the deposit, and/or a multilayered geometry with alternating layers of ice and dry regolith. A discrepancy is also discussed in that the neutron data suggests more hydrogen in the north yet Clementine data suggests that there is more area of permanent shadow in the south. Possible explanations are that all the excess hydrogen is not in the form of water ice, or perhaps the Clementine data is incomplete (the south pole was observed by Clementine in the winter, so some regions may receive sunlight in the summer)[3].

Stacy et al. (1997) used the Arecibo 12.6-cm radar system with a resolution of 125 m to map the lunar polar regions[4]. No areas greater than 1 square km were found with properties suggestive of the presence of ice. Several areas smaller than 1 square km were found with such properties but some of these areas were in sunlight and therefore the signals are likely not attributable to water ice. The observed high backscatter comes from steep crater walls as opposed to the crater floor in several cases. These observations suggest that these are regions of rough surfaces and/or blocky areas rather than ice deposits. Stacy et al. (1997) report that the Clementine radar data is consistent with but not unique to the presence of ice deposits[4]. Rock surfaces rough on the scale of the radar wavelength and observed at high incidence angles can result in similar signals[4].

Campbell (2003) used the Arecibo telescope at 70 cm for 300 m resolution to image the lunar poles[5]. Areas of crater floors near the poles did not yield strong radar echoes. Thus any lunar ice (if present) must be in the form of distributed grains or thin layers (cm or less in thickness). This scenario could satisfy the Lunar Prospector results without strong radar backscatter enhancement[5].

Campbell and Campbell (2005) used the Arecibo and Greenbank telescopes at 70 cm and 450 m resolution for latitudes 60 degrees S through 90 degrees S on the Moon[6]. Radar variations were attributed to variations in the surface and subsurface rock populations. Small areas of enhancement were observed on shadowed and sunlight terrain plus associated with small craters. High CPR values were observed in patchy clusters on the floors of both shadowed and sunlit craters. Based on Lunar Orbiter photographs, high resolution radar data, and the radar scattering properties of terrestrial rugged terrain, the lunar patterns are likely due to proximal ejecta blankets of abundant small craters. Due to this distribution, the radar signals were not interpreted as signals of ice[6].

The Clementine bistatic radar data was reanalyzed by Simpson and Tyler (1999) and these researchers were unable to reproduce the results of Nozette et al. (1996).

Any observed backscatter enhancements were not unique to the south pole and the observations were "easily attributable" to local terrain variations, topography, surface roughness, etc[7]. Thus this data was not interpreted as an indication of water ice deposits[7].

Campbell et al. (2006) presented new 20 m resolution, 13 cm wavelength data from Arecibo of the lunar south polar region[8]. They found no evidence for concentrated deposits of water ice in Shackleton Crater or elsewhere near the south pole. Instead the polarization properties that might normally be attributable to ice were found at all the observed latitudes and were strongly correlated with the rocky walls and ejecta of young craters[8]. In addition, no correlation was found between polarization and degree of solar illumination. If the polar hydrogen is in the form of water ice, this Arecibo data suggests the ice is only present as disseminated grains in the lunar regolith[8].

In addition, modeling results of potential water ice deposits in lunar cold traps was presented by Crider and Vondrak (2003)[9]. This study simulated the evolution of a water column in a lunar cold trap over time as a function of depth with water arriving from both the solar wind and from comets. Their results suggest that the regolith would reach an equilibrium concentration of water at 4100 ppm (0.41% per unit mass). This equilibrium value would be reached from solar sources alone and comets essentially are superfluous. Time merely increases the thickness of the layer in which ice will be harbored. In one billion years the layer would be 1.6 m thick and the ice would be diffuse. These model results are consistent with Arecibo observations and within a factor of two of the Lunar Prospector neutron spectrometer values[9].

The Lunar Reconnaissance Orbiter (LRO) and the Lunar Crater Observation and Sensing Satellite (LCROSS) will be launched in late 2008, and should provide the most definitive measurements yet. In the event that LRO and LCROSS both detect water ice (or if the results are ambiguous), follow-on missions may be required to ground-truth the presence/absence of water ice in the permanently shadowed regions(s) near the pole(s).

Mission Concepts

We consider four possible mission scenarios to investigate the potential presence of water ice in the permanently shadowed regions near the lunar poles, including including 1) penetrators / darts carrying relevant instrumentation, 2) a kinetic impactor mission with observations of resultant ejecta plume (e.g. LCROSS), 3) a soft lander capable of landing in permanent shadowed crater 4) a soft lander with mobility capability.

Penetrators/Darts. Small probes could expand the search for water to a wider variety of geographic and topological features. Penetrators (to probe the subsurface) and/or small egg-shaped surface probes could be These probe options could be delivered from 1) a lander located at the rim of a crater or permanently shadowed region (requires precision landing), 2) a cannon to fire the probes into dark regions, or 3) an orbital asset flying over the region of interest. Potential instruments that could be included on the probes to detect water ice include small neutron spectrometers (to determine hydrogen concentration in a one cubic meter probed volume) and / or a NIR spectrometer using tunable laser diode that measures water presence and concentration)).

Kinetic impactor. The LCROSS mission is slated for launch in late 2008 and will impact the Moon in 2009. This mission will excavate a crater in a permanently shadowed region while a shepherding spacecraft as well as ground and space-based observatories measure the resulting plume to search for water ice and vapor. LCROSS will provide information regarding the water ice content of two closely spaced regions on the Moon (LCROSS plans for two impacts: the Earth Departure Upper Stage of the launch vehicle and the Shepherding Spacecraft). Therefore a second LCROSS mission could be flown to search for water ice in a different region of permanent shadow near the north or south pole of the Moon.

Soft lander. A soft lander could land in a permanently shadowed region and make water measurements for several hours plus has the option of using an extra payload mass for extra batteries for power. Instrumentation includes a neutron spectrometer on the lander deck to measure hydrogen concentration and also an instrumented mole and/or drill to detect subsurface ice as a function of depth. In addition, the lander could carry electromagnetic sounder to measure the regolith density profile with the depth. It could also perform electrostatic measurement with the dielectric probe that is an indicator of water ice presence.

Soft lander with mobility capability. This option is similar to the soft lander but is able to traverse the lunar surface. The lander could make water measurements in a dark region and then use propellant to move to the next site, maximizing the mission design to visit as many different sites as possible. Possible additions include an instrumented footpad to collect contact measurements and/or spikes on the lander feet to obtain subsurface measurements. Instrumentation includes 1) neutron spectrometer on lander deck, 2) footpad laser ablation, 3) electrostatic measurement for contact measurement, 4) instrumented mole and/or drill for subsurface water measurements potentially made with diode laser water sensor.

THEME 2: RADIATION SHIELDING

The efficacy of using regolith for radiation shielding to the full range of radiation types and energies on the Moon are currently modeled but unconfirmed by experiment. In-situ measurements of radiation shielding are required to validate models since these shielding properties may be important for enabling human exploration. An ideal mission would be to equip a soft lander with an instrumented drill or mole that is capable of making radiation measurements at one or more depths in the subsurface.

Mission Concept

A soft lander equipped with a mole would be an ideal platform for measuring *in situ* the radiation shielding capabilities of the lunar regolith. A mole instrumented with radiation detectors (e.g. Radfet integrating dosimeter and/or PIN diode) would provide the needed measurements. Different levels of metal could also be added in front of the radiation detector to create a crude radiation spectrometer. To correlate high-Z particles, a spectrometer on the lunar surface is required. Target measurement depth with the mole is two meters.

THEME 3: BIOLOGIC EFFECTS OF LUNAR ENVIRONMENT

The biologic effects of the lunar environment should be understood before sending humans to the Moon for long durations. In addition, unique microbial ecologies develop in space habitats and must be understood as they interact with humans. We propose several mission concepts to address these issues including 1) study of organisms in the lunar environment (orbital and/or landed), 2) activation of dormant organisms during a solar particle event to specifically conduct studies during the higher flux of SPE, 3) addition of dust to surface samples to assess biologic effects of dust, 4) plant growth experiments (orbital and landed), 5) study of multiple generations of rats raised in lunar gravity.

Science experiments designed to investigate the Moon's combined environmental effects on biological organisms are well matched to the constraints inherent in a small lunar surface probe. Such studies are likely to yield important new insights affecting crew health during long-duration visits on the lunar surface. Based on previous heritage gained through payloads on free-flyers and the International Space Station, we know there are many <10 kg experiments of biological interest. Incorporating multiple experiments on a single small lunar lander is not only feasible, but practical.

Researchers will study the combined effects of radiation, low gravity, dust, light and thermal conditions on a variety of life forms, ranging from genes, proteins and microbes to Drosophila (fruit flies) and plants. These experiments will yield data relevant to membrane damage, cell growth, and DNA damage in the space environment. Environmental parameters can be controlled autonomously and lunar surface experiments would require only modest adaptation of existing payloads.

Mission Concepts

GeneSat derivative (orbital or landed). GeneSat-1 was launched in December 2006 and successfully achieved all of its technical objectives. The spacecraft has also returned scientifically useful data regarding the growth of E. Coli in a space environment. GeneSat-1 could be adapted to provide direct measurements of biologic response to radiation and microgravity en route to the Moon, radiation and 1/6 g at the Moon, and/or radiation and 1/6 g and the lunar dust environment. If dust is to be added to the biologic samples then some organisms will require an airlock whereas others can withstand vacuum if dehydrated and/or dormant..

GeneSat derivative (orbital or landed) correlated with SPE. A payload based on GeneSat-1 could be flown with dormant organisms that are then "activated" during a solar particle event (SPE) to specifically conduct studies during the SPE.

Plant Growth Experiments. Plants are complex terrestrial biological organisms and are superb models to send to the Moon in precursor biology experiments. Arabadopsis is often studied as a model organism and is an ideal candidate for initial plant growth experiments on the Moon. Lunar plant growth chambers can be designed from a number of derivative samples of space hardware including GeneSat-1 and plant chambers that have flown on the Space Shuttle and International Space Station.

"Translife" Mission Derivative: Higher-level organisms such as mice and rats could also be flown to

the Moon. Animal chambers suitable for spaceflight are currently being developed at NASA Ames Research Center and could provide data on multiple generations of organisms.

THEME 4: DUST AND REGOLITH CHARACTERIZATION

Dust and regolith must be understood in terms of chemical reactivity, biologic effects of reactivity, and effects on mechanical and other engineering systems. Several mission concepts include 1) orbiter to characterize lofted dust (including dust particle size, mass, charge, velocity, and composition) as well as dust lofting processes in association with solar activity, 2) orbiter which also characterizes the chemical reactivity of captured dust, 3) landed package with multiple dust assessment instruments addressing issues such as dust surface free radical activity and effects of hydration, energy of hydration, composition, surface pKa (acid/base), reactivity to specific materials, and kinetics of surface reactivity deactivation on exposure to (mock) wet biological tissue.

Background

Early measurements from the Surveyor, Lunokhod, Clementine, and Apollo missions to the Moon each returned evidence suggestive of the levitation of dust particles above the lunar surface. Subsequent theoretical modeling suggests that such levitation is possible due to the differential charging of the lunar surface. Theory predicts that dust levitation events should be correlated with the day-night transition on the Moon and indeed most data indicates that dust activity increases near the terminator. The phenomenon of dust levitation is therefore of high scientific interest and additional data is required to more fully understand the cause and effect of this dust transport mechanism.

In addition to the scientific interest in studying lunar dust transportation processes, dust is an insidious problem for human exploration. Therefore, information gleaned from these studies will also be useful for mitigating adverse dust effects in relation to human exploration. The lunar dust is potentially detrimental for several reasons including: 1) the small, angular particulates are especially harmful to humans, 2) fine particles are harmful to hardware components, joints, etc. (even on the relatively short stay Apollo missions hardware components were severely compromised by lunar dust contamination), and 3) large acreage surface (like solar panels and radiators) may be gradually covered with lunar dust, thus diminishing their effectiveness in generating electricity or dissipating heat, and 4) incoming high velocity particles (e.g. 30 km/s), though thought to be infrequent, could prove fatal if impacting a critical component (such as an astronaut face shield).

This paper therefore discusses several mission scenarios (including robotic orbiter, robotic lander, and astronaut deployed concepts) to measure: 1) the dust transport due to human activities on the lunar surface, 2) the time dependence of dust lofting rates and the impact direction correlated with the lunar day / night cycles, 3) the vertical distribution of lofted dust properties, 4) the infall rates of cometary and asteroidal interplanetary dust particles, and 5) in situ dust properties.

Many small airless bodies in the Solar System are covered with a dusty regolith and therefore the processes causing lunar dust transport (electrostatic charging) may also operate on bodies such as asteroids, other planetary satellites, Mars, etc. Thus the information acquired through these lunar studies could also be applied elsewhere in the Solar System.

Dust Levitation Mechanism

It is believed that the levitated dust on the Moon observed by Surveyor, Clementine, Lunokhod, and Apollo is mainly caused by differential charging of the lunar surface near the terminator. The dust particles become electrostatically charged due to the Moon's interaction with the surrounding plasma environment as solar ultraviolet and x-ray radiation cause the photoemission of electrons from lunar surface materials[10]. Most of these emitted electrons escape from the lunar surface and thus the surface becomes positively charged[11]. A layer of positively charged dust can then form in the lunar vacuum above the negative space field charge of the electron cloud[11]. On the lunar night side the plasma electron currents dominate (electron driven) and so the surface charges negative[10, 12]. Such a model can account for dust levitated on the order of decimeters to meters above the lunar surface[12].

To account for the observations of grains at ~100 km altitude, Stubbs et al. (2006) present a dynamic "fountain" model that explains how sub-micron dust is lofted up to 100 km above the lunar surface[13]. In this model the charged dust grains follow ballistic trajectories, subsequent to being accelerated upward through a narrow sheath region by the surface electric field[13]. This dynamic dust grain fountain model predicts that sub-micron sized dust grains would be lofted to altitudes of 0.1-100 km at the terminator.

Laboratory studies also support the notion of dust levitation on the Moon. Sickafoose et al. (2001) performed levitation experiments on dust grains in a low density plasma[14]. Their results show that: 1) grains can levitate in a plasma sheath above a conducting surface, 2) levitating grains can reach a height corresponding to that predicted by theory, and 3) a mechanism to inject grains into a sheath is not required if the electric field is sufficiently strong[14].

Mission Concepts

For the proposed mission concepts we intend to measure: 1) the dust transport due to human activities on the lunar surface, 2) the time dependence of dust lofting rates and the impact direction correlated with the lunar day / night cycles, 3) the vertical distribution of lofted dust properties, 4) the infall rates of cometary and asteroidal interplanetary dust particles, and 5) in situ dust properties.

We also intend to define measurements to quantify the differences between dust lofted through natural electrostatic effects and dust lofted due to astronaut activity on the lunar surface. Understanding the different effects of both of these dust transport mechanisms is of high scientific importance and is also critical to enable human exploration on airless, dusty planetary bodies.

Robotic Orbiter. One mature concept for a low-cost orbiter is the Lunar Science Orbiter (LSO). This mission will characterize dynamic processes that cause lifting and transport of lunar dust, and the dependence of this activity on solar illumination and the local space environment. LSO can assess lunar surface charging in response to solar and plasma environment, dust transport and dusty plasmas/exosphere, map the surface composition and volatiles and provide knowledge regarding fundamental space plasma physics and lunar-solar interactions.

Robotic lander. There are multiple instruments that could be utilized on the lunar surface to characterize the lunar dust. A static lander could provide measurements at one location whereas a lander platform with mobility capability can characterize the lunar dust at multiple locations. In situ measurements of dust composition, particle size distribution, surface reactivity, adhesion properties, thermal properties, magnetic properties, and conductivity could be obtained by a robotic lander. The primary dust distribution and properties instrument would be an optical sensor that measurement dust scattering properties across range of phase angles and particles (wavelength) sizes. This instrument can be either passive (relying on scattered sunlight) or active (lidar) instrument.

Astronaut Deployable Experiments

"*No pest strip*". The "no pest strip" concept is to deploy vertical strips of various materials to which lunar dust might adhere in order to obtain vertical profiles of dust lofting (similar to "no pest strips" that cause insects to stick to the hanging strip). The no pest strip will also assess the relative "stickiness" of the lunar dust. Due in part to the changing mass to surface area ratios of different sized particles, we anticipate that a size dependence may exist regarding the adhesion efficiency of lunar particles. We also anticipate that different components of lunar fines may preferentially adhere to different types of materials (for example, one of the best dust collectors during Apollo was the spacesuit material).

Aerogel Canister. Aerogel canisters will be used to record high velocity particles (e.g. 30 km/s) that impact the lunar surface. These measurements will record the infrequent but potentially deadly high velocity particles and, at least for the lower velocity particles, provide material for compositional analysis [5]. One container will be placed on the lunar surface near the human base and the second container will be placed at a site further away from the base which is not affected by human surface operations. Ideally at least one of the aerogel canisters (namely the canister closest to the human base) would be returned to Earth for detailed study in the laboratory and the second canister (located away from the human base) could remain on the lunar surface to continue gathering data and be returned to Earth on a subsequent mission. In a manner similar to the return of the "no pest strip", care must be taken to ensure the aerogel collectors are not expose to contamination.

Rollout carpet. The rollout carpet concept consists of a material (similar to solar panel material used on rooftops, although the precise nature of this material will be assessed during this proposed study) that will be rolled out across the lunar surface to cover a large surface area and return to Earth a record of the particles striking the lunar surface. The carpet will record two types of dust arrival: 1) incoming hypervelocity cometary and asteroidal particles and 2) local lofted dust. The hypervelocity particles will likely vaporize upon impact and so will be evidenced by small craters on the detector. The lofted dust will be evidenced by grains collected on the carpet. Through this study we will assess the most beneficial collection materials to use with regards to ease of deployment, efficiency of dust capture, and mass considerations.

Dust sensors (impact rate and direction). These dust sensors would be similar to the LEAM experiment in that impact rates and directionality will be measured. A timing device will be included to measure impacts as a function of time and several sensors can be mounted in different orientations to measure the azimuth of incoming dust particles. We will evaluate the LEAM mechanism and evaluate the engineering design, making note of LEAM components that failed (e.g. thermal control malfunctioned, dust cover deployment occurred late, etc). These sensors are also the only proposed instruments with power, thermal, and communications requirements (the remaining instruments are passive sensors) and we will evaluate each of these requirements.

THEME 5: ENABLING LUNAR ASTROPHYSICS

The Moon has been suggested as a prime astronomical observing platform. Potential precursor missions include 1) lander to measure sky brightness and dust activity, 2) orbital asset to monitor dust transport, 3) lander and/or orbital platform to assess radio interference on lunar farside for very low frequency observations.

Background

A variety of different types of lunar observatories have been proposed over the years and a long list of potential advantages/disadvantages over terrestrial sites has been compiled[14, 15, 16]. Regardless of the type of observatory being considered, one of the most important first steps will be a thorough site survey of the proposed lunar location. A small spacecraft can evaluate the site in significant detail, providing input to enable a precision landing and a determination of the environmental effects at this location.

Lunar Observatories

There is vigorous and ongoing debate within the scientific community over the advantages and disadvantages of conducting astronomical research from the Moon[14, 15, 16]. The absence of a substantial lunar atmosphere has long tantalized astronomers, particularly at optical wavelengths. However, the extent to which lunar dust may scatter light at optical and ultraviolet wavelengths, or introduce added thermal effects at infrared wavelengths, remains unknown. The ultimate answer(s) on the conditions and suitability of the lunar surface for astronomical purposes will not be known until we go there with the express purpose of investigating this question. In this sense, the Moon is no different than the South Pole or the high Atacama plains. Before investing substantial resources in building and operating astronomical instruments, it behooves us to assess the quality of the site and to understand the technical challenges in building and commissioning astronomical instruments on the Moon.

"Peaks of eternal light" in the lunar polar regions are gaining increased scrutiny as potential sites for human outposts. These mountaintops, surrounded by permanently shadowed craters, are bathed in permanent solar illumination. These locations thereby offer an ideal mix of constant solar energy on the peaks and potential water ice in the deep craters. From an astronomical perspective, the poles offer a zenith view fixed on the sky along the (lunar) spin axis. Thus, a zenith (or transit) telescope design makes it possible to consider larger apertures with fewer structural movements. Such a telescope would provide very deep integrations, with no telescope steering, for high sensitivity studies of the distant universe.

Mission Concepts

There are multiple measurements that could be collected to help assess the fidelity of the Moon as an astronomical platform and also to assist with site selection for a lunar observatory.

To assess the viability of the Moon as an observatory base, a precursor lander mission could measure sky brightness at optical and infrared wavelengths and also make dust measurements at the site(s) of interest. An orbital asset could also assess the physical details of dust lofting events which could be detrimental to sensitive telescope equipment. An orbital mission could also explore the feasibility of a very low frequency (VLF) telescope on the radio-quiet lunar farside by quantifying the radio-quiet nature of the Moon. The VLF telescope possibility could also be assessed by a lander on the lunar farside equipped with dipoles (10 kHz to 500 kHz) to measure actual interference on the lunar surface.

CONCLUSIONS

There are a multitude of significant lunar missions which could be conducted by small spacecraft. Each of the mission scenarios described here in the categories of 1) Water, 2) Radiation Shielding, 3) Biologic Effects of Lunar Environment, 4) Dust and Regolith Characterization, and 5) Enabling Lunar Astrophysics could be accomplished using a small spacecraft platform. Based on the work presented here, significant attention should be paid to further consideration of the important potential contributions of small spacecraft to lunar science and exploration.

References

1. Nozette, S.. Spudis, P.D., Robinson, M.S., Bussey, D.B.J., Lichtenberg, C. and R. Bonner, "Integration of Lunar Polar Remote-sensing Datasets: Evidence for Ice at the Lunar South Pole," J. Geophys. Res., vol. 106, Issue E10, 2001.
2. Nozette, S., Lichtenberg, C.L., Spudis, P., Bonner, R., Ort, W., Malaret, E., Robinson, M. and E.M. Shoemaker, "The Clementine Bistatic Radar Experiment," Science, vol. 274, No. 5292, 1996.
3. Feldman, W.C., Maurice, S., Binder, A.B., Barraclough, B.L., Elphic, R.C., and D.J. Lawrence, "Fluxes of Fast and Epithermal Neutrons from Lunar Prospector: Evidence for Water Ice at the Lunar Poles," Science, vol. 281, No. 5382, 1998.
4. Stacy,N.J.S., Campbell, D.B., and P.G. Ford, "Arecibo Radar Mapping of the Lunar Poles: A Search for Ice Deposits," Science, vol. 276, No. 53118, 1997.
5. Campbell, B.A., Campbell, D.B., Chandler, J.F., Hine, A.A., Nolan, M.C., Perillat, P.J., "Radar Imaging of the Lunar Poles," Nature, vol. 426, 2003.
6. Campbell, B.A. and D.B. Campbell, "Regolith Properties in the South Polar Region of the Moon from 70-cm Radar Polarimetry", Icarus, vol. 180, 2006.
7. Simpson, R.A. and G.L. Tyler, "Reanalysis of Clementine Bistatic Radar Data from the Lunar South Pole," J. Geophys. Res., vol. 104, No. E2, 1999.
8. Campbell, D.B., Campbell, B.A., Carter, L.M., Margot, J., and N.J.S. Stacy, "No Evidence for Thick Deposits of Ice at the Lunar South Pole," Nature, vol. 443, 2006.
9. Crider, D.H. and R.R. Vondrak, "Space Weathering Effects on Lunar Cold Trap Deposits," J. Geophys. Res., vol. 108, No. E7, 2003.
10. Manka, R.H., "Plasma and Potential at the Lunar Surface," Proceedings of the ESLAB Conference on Photon and Particle Interactions in Space, Noordwijk, Netherlands, 1973.
11. Foldi, T. and S. Berczi, "Electrostatic Modeling of the Lunar Soil," Acta Mineralogica-Petrographica, vol. 43, 2002.
12. Stubbs, T.J., Vondrak, R.R., and W.M. Farrell, "A Dynamic Fountain Model for Lunar Dust," Adv. Space Res, vol. 37, 2006.
13. Sickafoose, A.A., Colwell, J.E., Horanyi, M., and S. Robertson, "Experimental Investigations on Photoelectric and Triboelectric Charging of Dust," J. Geophys. Res., vol. 106, No. A5, 2001.
14. Burke, B., "Astrophysics from the Moon," Science, vol. 250, No. 4986, 1990.
15. Lowman, P.D., "Astronomy from the Moon: A Second Look," Mercury, vol. 29, No. 2, 2000.
16. Lester, D.F., Yorke, H.W., and J.C. Mather, "Does the Lunar Surface Still Offer Value as a Site for Astronomical Observatories?," Space Policy, 2004.