Integration of lunar polar remote-sensing data sets:
Evidence for ice at the lunar south pole

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Abstract. In order to investigate the feasibility of ice deposits at the lunar south pole, we have integrated all relevant lunar polar data sets. These include illumination data, Arecibo ground-based monostatic radar data, newly processed Clementine bistatic radar data, and Lunar Prospector neutron spectrometer measurements. The possibility that the lunar poles harbor ice deposits has important implications not only as a natural resource for future human lunar activity but also as a record of inner solar system volatiles (e.g., comets and asteroids) over the past billion years or more. We find that the epithermal neutron flux anomalies, measured by Lunar Prospector, are coincident with permanently shadowed regions at the lunar south pole, particularly those associated with Shackleton crater. Furthermore, these areas also correlate with the $\beta = 0$ circular polarization ratio (CPR) enhancements revealed by new processing of Clementine bistatic radar echoes, which in turn are colocated with areas of anomalous high CPR observed by Arecibo Observatory on the lower, Sun-shadowed wall of Shackleton crater. Estimates of the extent of high CPR from Arecibo Observatory and Clementine bistatic radar data independently suggest that $\sim 10$ km$^2$ of ice may be present on the inner Earth-facing wall of Shackleton crater. None of the experiments that obtained the data presented here were ideally suited for definitively identifying ice in lunar polar regions. By assessing the relative merits of all available data, we find that it is plausible that ice does occur in cold traps at the lunar south pole and that future missions with instruments specifically designed to investigate these anomalies are worthy.

1. Introduction

The lunar poles have long been theorized to harbor ice deposits in permanently shadowed regions because these regions can act to cold trap volatile compounds, including water introduced into the lunar environment [Watson et al., 1961]. This is a fascinating possibility both because such deposits would serve as a natural resource for future human lunar activity and because the plausible sources of lunar water (e.g., comets and asteroids) are of inherent interest. In fact, modeling the temperatures of shadowed craters near the poles [Ingersoll et al., 1992; Salvail and Fanale, 1994; Vasavada, 1998] shows temperatures low enough to cold trap materials substantially more volatile than water ice. Studies of the transport and retention of water ice and other volatiles also support the possibility of water ice being present at the pole [Butler, 1997; Morgan and Shemanskky, 1991]. The latter work suggested that sputtering was rapid enough to destroy slow continuous deposits of water ice, for example, from micrometeorite water, or water produced from reduction of lunar surface materials to produce water from solar wind hydrogen but that thick deposits of ice introduced by comets or large "wet" asteroids might survive by sequestering of ice by regolith overturn.

No conclusive evidence of water ice currently exists, but several data sets provide evidence that is suggestive of the presence of water. The least equivocal of these data sets are the results of the Lunar Prospector [Binder, 1998] neutron spectroscopy experiment, which shows the presence of regions of anomalously low epithermal neutron flux near the lunar poles [Feldman et al., 1998, 1999]. The low neutron flux is interpreted to be due to the presence of hydrogen, which moderates neutron energies efficiently. While a solar wind source for these hydrogen anomalies cannot be ruled out, water ice is a plausible carrier of this hydrogen.

The startling discovery of deposits with radar properties consistent with water ice at the poles of Mercury [Harmon et al., 1994], also associated with permanently shadowed craters, led to several radar measurements of the lunar poles in the hopes of detecting similar deposits. These results are much more equivocal than the Mercury results. Initially, Arecibo monostatic circular polarization ratio (CPR) radar observations in the region of the lunar south pole were interpreted to possibly indicate the presence of ice deposits on the lower Earth-facing interior wall of Shackleton crater [Stacy, 1993]. Data collected by the Clementine bistatic radar experiment [Nozette et al., 1996, 1997; Lichtenberg, 2000] also revealed anomalous polarization ratios in the Shackleton region, suggesting the presence of patchy, "dirty" ice deposits. Subsequently, the same Arecibo data utilized by Stacy [1993] were reported to be inconsistent with this interpretation [Stacy et al., 1997]. There it was suggested that all anomalous high CPR areas observed by Arecibo, near the lunar south pole, were caused by rough surfaces, as only some portions of the anomalies were believed to be permanently shadowed. Additionally, Simpson and Tyler [1999] postulated that the Clementine polarization anomaly was due to roughness and/or random noise in the data and not by the presence of ice. These radar results, which are still a matter of some controversy [Nozette et al., 1998], have led some workers to...
the general conclusion that the Mercury polar cold traps are "full" while the lunar cold traps are "empty" [e.g., Vasavada, 1998]. The "Moon empty, Mercury full" interpretation rests heavily upon the radar and may not be warranted after considering all the available data. In fact, observations of the lunar poles from the Earth for detection of ice are greatly hampered by the grazing incidence angle. At these incidence angles the reflectivity enhancement and polarization anomalies caused by the Coherent Backscatter Opposition Effect (CBOE) in the presence of ice are largely suppressed. It is little recognized that the observations of Mercury's poles are at a much more favorable geometry than observations of the Moon, so a weak detection or nondetection at the Moon does not necessarily exclude the presence of localized Mercury-like deposits. In addition, much of the lunar poles remains in radar shadow, so no conclusions can be drawn from these regions regarding radar properties. Such deposits could be detectable from Earth on crater walls which have lower local angle of incidence (e.g., Shackleton).

The interpretation of these data sets in the context of the possible presence of water ice requires careful intercomparison of the data. For example, the suggestion by Feldman et al. [1998] that 1% water ice by weight might be present at the south pole is dependent upon the estimate of total area of permanent shadow within the neutron anomaly; the actual value of the detected anomaly suggests much lower abundances (at the 60 km resolution of the experiment). This paper will present all available data sets (Lunar Prospector neutron data, Arecibo radar, lighting estimates of permanent shade based on analysis of Clementine imaging, and the Clementine bistatic radar experiment) relevant to the question of lunar polar ice, all coregistered to a newly updated lunar cartographic control system for the lunar poles. Less accurate control networks hampered previous analyses [e.g., Stacy et al., 1997]; thus we use an improved control network [Bussey et al., 1999a, 1999b] to compare data. We will also show the interior wall of Shackleton crater to be unique. Both the Clementine and Arecibo reported radar anomalies are coincident with permanent

Plate 1. Overall view of the lunar south pole showing locations of Clementine radar sampling targets for orbits 234 and 235 overlain on an Arecibo radar reflectivity image [Stacy, 1993]. The frequency spectra were collected during analysis into 4 s wide bins within which each frequency bin was 3.05 Hz wide. The width of the colored regions along the beta zero track depicts the overlap of all bins containing the targets during the almost 200 s that each was within ±1° of β = 0°. The breadth of the colored regions across track is the limit of the ±1° constraint; blue to red represents 1° to 0°, respectively. The yellow lines indicate the β = 0° track for each orbit, and the red circle shows the approximate size of the Lunar Prospector 2° data [Feldman et al., 1999, 2000]. S indicates the location of Shackleton crater; U1 and U2 refer to craters called out by Feldman et al. [2000] as possible sources of neutron spectrometer anomalies.
Plate 2. (a) Clementine bistatic radar response plots and sampled regions for targets 1–4 from orbit 235 overlain on the Arecibo radar image shown in detail (see overall location and explanation in Plate 1). Orbit 235 radar sampling regions contain little to no resolved permanently shadowed regions and thus serve as control for data from orbit 234. (b) Clementine bistatic radar targets 14–17 from orbit 234. Note the gradual increasing and sharpening of the signal as the $\beta = 0$ track passes over Shackleton crater, the same region where Arecibo right circular polarized (RCP) data first showed the crater wall to be anomalous [Stacy, 1993]. On the response plots, the solid line represents the circular polarization ratio (CPR), and the top dashed line is left circular polarized (LCP), while bottom dashed line is RCP (for all plots in Plates 2a and 2b). The rest of the orbit 234 and 235 samples are presented in Appendix A.
Plate 2. (continued)
shadow derived from Clementine imaging and the hydrogen anomaly detected by Lunar Prospector. This integrated data set can be used to support future exploration of the poles from spacecraft or Earth-based observations.

2. Description of Data Sets

2.1. Control Network

Previous correlations of radar features and shadowed terrain were not optimal because of the preliminary control networks then available. Specifically, Arecibo radar images of the poles were tied to the Lunar Orbiter control network [Stacy et al., 1997], resulting in poor correlation when comparing features observed in Clementine and Arecibo radar data, resulting in mislocation of more than 10 km [Bussey et al., 1999a]. During construction of illumination maps it was determined that the previous U.S. Geological Survey (USGS)-RAND global Clementine control network [Edwards et al., 1996] was not optimal within a few degrees of the poles [Bussey et al., 1999a, 1999b]. In order to locally improve the network, Arecibo radar images (one each at the north and south poles, from Stacy et al. [1997]) that represented the maximum surface coverage of the polar regions (from 80° to the pole on the nearside, with lesser coverage on the farside) available in single images were used. They were controlled to the USGS basemap [Edwards et al., 1996] in the vicinity of 80°–85°, where the global control network is more reliable. Near the poles (85°–90°) the Clementine images were then tied to the newly controlled radar images [Bussey et al., 1999a, 1999b]. Subsequent improvements in the polar control network and the addition of Clementine High-
Resolution Camera (HRES) image data allowed improved limits to be placed on the location and distribution of permanently shadowed terrain [Bussey et al., 1999a, 1999b].

2.2. Lunar Prospector Neutron Spectrometer Data Set

Lunar Prospector neutron spectrometer data sets were obtained at low altitude (30 km) during the extended mission [Feldman et al., 1999], including both epithermal and fast neutron flux measurements. We coregistered and plotted as a color-coded map the epithermal neutron counts arising from latitude/longitude cells projected on the lunar polar regions. The resolution of these data is \( \sim 60 \) km.

2.3. Solar Illumination Data Set

Bussey et al. [1999a, 1999b] created an illumination map by coadding all the images near the pole that had common overlap and then looking for areas that receive no illumination, enabling better isolation of areas likely to be in permanent shadow. Their best current estimate of the maximum extent of shadow at the south pole is 3300 km\(^2\) within 1.5\(^\circ\) of the pole. An initial estimate for the north pole was 530 km\(^2\) [Nozette et al., 1996] based on the area of a few craters close to the pole that appear to be permanently shadowed. Subsequent work has shown that features such as small crater floors and north-facing crater rims might be in permanent shadow [Bussey et al., 1999b]. This appears to be true for features all the way out to 80\(^\circ\)N. A preliminary darkness map shows that there are numerous small outcrops of shadow with a total area of \( \sim 10,000 \) km\(^2\) within 10\(^\circ\) of the north pole [Bussey et al., 1999b].

2.4. Clementine Bistatic Radar Data Set

The Clementine bistatic radar experiment and data processing methodology is described in detail by Lichtenberg [2000]. This experiment measured the radar-scattering properties of the lunar surface as a function of bistatic angle \( \beta \) (the angle subtended by the radar boresight and the sub-Earth vector at the lunar surface [see Nozette et al., 1996, Figure 1]). Initial analysis of the bistatic radar data [Nozette et al., 1996] used averages over broad areas of polar terrain. New processing has improved the spatial resolution and allows geographic correlation of anomalies with specific terrain features. Plate 1 shows the locus of points sampled by Clementine during orbits 234 and 235. These data are overlaid on top of an Earth-based radar image in order to provide geographical context. The Clementine bistatic radar data was dynamically processed to extract an average CPR versus \( \beta \) for specific surface areas [Lichtenberg, 2000]. The areas that contain the \( \beta = 0 \) track were sampled at a range of \( \beta \) angle. To detect CBOE, terrain must be sampled around \( \beta = 0 \pm 1^\circ - 2^\circ \). Only CBOE originating from terrain visible by the Earth receiving stations, lying along the Clementine \( \beta = 0 \) ground track, will be detectable in the Clementine bistatic radar data set. Rainbow-colored areas (Plates 1, 2, and Plate A1) show the regions sampled where \( \beta \) has a value between +1\(^\circ\) and -1\(^\circ\), with terrain sampled at minimum beta lying under the \( \beta = 0 \) track, for orbit 234 and orbit 235. The most reliable CBOE measurements come from the center of these regions. The colored horseshoe-shaped areas represent the territory over which the average sample was taken over time. Orbit 235 does not sample any area a significant polar shadowed terrain and thus serves as a control orbit.

Plates 2a and 2b show some of the bistatic radar results in more detail (the remaining sample sites are presented in Appendix A for completeness). These data indicate the nature of the radar return for several of the sampling stations the both orbit 234 and orbit 235. Target 17 in orbit 234 covers the Earth-facing inner wall of Shackleton crater. Plate 2b shows that target 17 has the highest enhancement of CPR at \( \beta = 0 \) of any of the Clementine targets. Target 16 in orbit 234, which covers a large fraction of the floor of Shackleton crater, as well as the inner wall that faces away from Earth (and therefore cannot be observed by Earth-based radar ground stations) also has a detectable CPR as \( \beta \) approaches zero.

2.5. Arecibo Monostatic Radar Data Set

The Arecibo monostatic right circular polarized (RCP), left circular polarization (LCP), and CPR images for the lunar south pole were first published by Stacy [1993]. These data give a much better picture of the geography around the pole than can be seen in the Clementine images owing to the large amount of solar shadowing. The shadowing at the south pole was at a maximum during the Clementine mission, as it was southern winter. Despite the poor viewing geometry of the lunar poles from Earth, the radar data can see into solar shadowed regions in many areas (Plate 3). Near the pole the radar advantage diminishes, and only a sliver of the solar shadowed area on the inner Earth-facing wall in Shackleton can be seen in the radar images [Stacy, 1993]. Of special interest are the areas of overlap between solar shadowed terrain and areas visible to Earth-based radar receivers. Such area(s) are the only possible sources of ice signals (if ice exists at the poles) in the radar data sets. The CPR image was thresholded to isolate CPR regions in the range 0.9-1.1 (Plate 3, bottom right) identified by Stacy [1993] as potentially emanating from ice-bearing materials. The largest concentration of the CPR anomalies is related to the Earth-facing inner wall of Shackleton. Examination of solar shadow data and the CPR map shows that \( \sim 46 \) km\(^2\) of solar shadowed terrain within Shackleton crater can be observed. This estimate is in agreement with independent estimates derived from ground-based radar interferometry topography [Margot et al., 1999].

3. Discussion

By combining the radar, illumination, and neutron spectrometer data sets, we can constrain the distribution and physical state of...
Plate 5. (a) Lighting map overlaid on Clementine UVVIS mosaic. The blue line indicates the Clementine orbit 234 $\beta = 0$ track; crater labels are the same as in Plate 1. (b) Epithermal neutron flux measurements from Lunar Prospector. The blue areas represent flux deficits, reflecting higher concentrations of hydrogen. South polar craters that contain permanently shadowed terrain are labeled along with Shackleton "S" (adapted from http://www.lunar.lanl.gov/) [see also Feldman et al., 1999].
putative ice deposits. The coregistered data sets are presented in Plates 3–5. Plate 4 consists of a south pole composite image of shadowed areas, the orbit 234 \( \beta = 0 \) ground track, and the Anticub CPR \( \approx 1 \) areas. Plate 5 shows the Lunar Prospector neutron spectrometer flux measurements from Feldman et al. [1999] with the location of Shackleton and neighboring craters also shown. The neutron data (Plate 5) show a general regional epithermal neutron deficit correlated with areas of permanent shadow at the poles [Feldman et al., 1998, 1999]. The Lunar Prospector neutron spectrometer data reveal three distinct anomalies associated with Shackleton crater and two adjacent craters [Feldman et al., 2000]. One of the three anomalous neutron spectrometer sample elements at the south pole covers a major portion of Shackleton crater (Plate 5). Approximately 1 km\(^2\) of relatively pure ice (10–20% regolith), with a shallow regolith covering 10–20 cm, should be detectable by the Clementine bistatic radar experiment [Simpson and Tyler, 1999]. Therefore a few percent of the Lunar Prospector estimated ice area should be detectable by Clementine bistatic radar, given favorable location and geometry.

The areas of high CPR (\( \sim 1 \)) observed by Arecibo occur in both shadowed and illuminated areas, as previously noted [Stacy et al., 1997]. However, these areas are not all identical in morphology and geological context. The large arrow in Plate 4 shows the largest area of contiguous high CPR on the lower wall of Shackleton crater. The correlation of the largest contiguous observed area of high CPR and the close coincidence of the Clementine orbit 234 \( \beta = 0 \) track are also shown in Plate 4. The largest area of contiguous high CPR is associated with the shadowed lower wall of Shackleton crater, which we estimate to be \( 10 \pm 6 \) km\(^2\) on the basis of a range of pixel counts and thresholds from the region. The \( \sim 1 \) dB, \( \beta = \pm 1^\circ \), bistatic CPR enhancement in target 17 (Plate 2b) is the most CBOE-like found in the Clementine bistatic radar data set. It also samples the same location (Plate 4), which contains the anomalous high CPR areas reported in the lower Earth-facing rim of Shackleton [Stacy, 1993]. Of the Clementine bistatic analysis targets, target 17 has the closest, nonoverlapping proximity to the Earth-facing wall of Shackleton crater. The area sampled by target 17, \( \beta = 1^\circ \), is calculated to be 5130 km\(^2\). This is the average of the sampled area for which \( \beta = \pm 1^\circ \) and for which a Doppler frequency bin coincides with that of target 17.

Target 17 is the target that best covers the Earth-facing inner wall of Shackleton, specifically including the areas of Arecibo high CPR. Plate 2b shows that target 17 has a high Clementine CPR enhancement approaching \( \beta = 0 \). Additionally, target 16 (Plate 2b) shows a noticeable Clementine CPR enhancement approaching \( \beta = 0 \). It covers a large portion of the floor of Shackleton as well as the crater wall that faces away from Earth (not visible from Earth-based radar receivers), both regions that are permanently shadowed and therefore possible locations of ice deposits. A series of targets (1–10) obtained during Clementine orbit 235 sample virtually no polar shadowed terrain, which is otherwise similar to the orbit 234 ground track terrain, in that both are cratered highlands (Plate 2a). Orbit 235 serves as a control area. These areas show no statistically significant (3\( \sigma \), 0.3 dB) \( \beta = 1^\circ \)CPR enhancements.

The method applied to estimating the fractional ice area on Mercury [Butler et al., 1993] was applied to target 17 (orbit 234, Plate 2b). Using the specific radar cross sections of average illuminated lunar surface measured during Clementine control orbit 235 for a region of latitude \(-80^\circ\) to \(-82^\circ\) and \( \beta = 1^\circ \), radar properties attributed to ice on Mercury, and the relative CPR enhancement in orbit 234 target 17 (1 \( \pm 0.3 \) DB), a fractional area for the observed ice surface area is estimated. The fractional ice area that could produce the observed target 17 \( \beta = 1^\circ \)CPR enhancement is \( \sim 10–16 \) km\(^2\). This estimate is in agreement with the area of anomalously high CPR observed in Shackleton crater by Arecibo (\( 10 \pm 6 \) km\(^2\)) and is an order of magnitude greater than the minimum Clementine detection threshold. It is likely the high CPR regions in Shackleton contribute to the average CPR enhancement reported by Nozette et al. [1996] and the sporadic CPR enhancements reported subsequently [Simpson and Tyler, 1999]. The Clementine bistatic CPR enhancement is largely due to enhanced RCP (Plate 2, Appendix A), suggesting that the high radar backscatter is due to CBOE (M. I. Mischenko, personal communication, 1997). RCP is more indicative of surface composition for measurements at large incidence angles (M. I. Mischenko, personal communication, 1997).

It has been argued on theoretical [Arnold, 1979; Ingersoll et al., 1992; Butler, 1997] and observational [Butler et al., 1993] grounds that “dirty” ice deposits are present in the permanently shadowed regions near the north pole of Mercury. It was suggested [Harmon, 1997] that if ice deposits of the magnitude postulated for Mercury are present on the Moon, they should be detectable by Earth-based radar. Feldman et al. [1998] argues that lunar polar radar ice measurements are indeterminate owing to a covering of high-FeO regolith (not found on Mercury). No direct compositional data exist for Mercury; however, remote-sensing measurements indicate that the Mercurian crust is most likely similar to lunar highlands material (low-FeO anorthositic material [Vilas, 1988; Sprague et al., 1994; Blewett et al., 1997]). Finally, FeO regolith content has been shown to have little effect on 13 cm radar observations probing similar depth as the neutron spectrometer measurements [Campbell et al., 1997].

An important difference between the lunar and Mercurian radar observations is the observing geometry. The relatively high angle of incidence of existing lunar radar measurements (\( \sim 85^\circ \) for Arecibo and Clementine versus \( \sim 70–80^\circ \) for Mercury) limits the observable shadowed area. More important, high radar incidence angles (\( \sim 85^\circ \)) and a slightly higher regolith mixing fraction will suppress the lunar polar CBOE effect [Mischenko, 1996a, 1996b] (Figure 1), so the suggestion by Harmon [1997] that lunar ice
Plate A1. Remainder of bistatic radar response plots and sampled regions for targets (a) 5–8 and (b) 9 and 10 from orbit 235 overlain on the Arecibo radar image (see overall location and explanation in Plate 1). Orbit 235 radar sampling regions contain little to no resolved permanently shadowed regions and thus serve as control for data from orbit 234. Targets 1–4 are shown in Plate 2. On the response plots, the solid line represents CPR, and the top dashed line is LCP, while the bottom dashed line is RCP.
deposits similar in character to those on Mercury should be detectable is not correct.

Summary and Conclusions

The coregistration of lunar south pole remote-sensing data sets shows the interior wall of Shackleton crater to be unique. Refined processing of the Clementine bistatic radar data into higher-resolution geographic bins shows that the highest bistatic CPR enhancement around $\beta = 0$ originates in this anomalous region in the lower Earth-facing wall Shackleton crater. The geographic coincidence of the Clementine bistatic $\beta = 0$ track directly with the Arecibo high CPR anomaly discovered by Stacy [1993] is coincident with the enhanced CPR observed by the Clementine bistatic radar experiment for orbit 234. Areal estimates of high CPR from pixel counts of Arecibo data, and independent estimates based on the Clementine radar results, using the fractional area of high CPR (0.9–1.0) required to yield the observed 1 dB CPR enhancement for the area sampled in Clementine target 17, are consistent. The bistatic dependence of CPR and RCP supports the conclusion that the high CPR observed in the monostatic and bistatic radar data sets, containing the lower Earth-facing wall of Shackleton, is suggestive of CBOE and therefore of "dirty" ice rather than wavelength-(centimeter-)scale roughness. When the high-resolution Lunar Prospector neutron spectrometer data [Feldman et al., 1999] are integrated with the radar and Sun shadow data sets, the results show that Shackleton crater is contained within the anomalous epithermal and fast neutron deficit region adjacent to the lunar south pole.

While the data set integration provides supporting evidence for the presence of ice on the lower wall of Shackleton [Stacy, 1993; Nozette et al., 1996], it is not conclusive. Corroboration of this hypothesis requires additional data. Earth-based radar experiments (as well as orbiters that use an Earth receiver, e.g., Clementine) are limited in that the surface visible from Earth represents only a small portion of the permanently shadowed terrain, e.g., <10% in the case of Shackleton. The grazing incidence angle means that CBOE is muted (Figure 1) and back and forward scattering mechanisms are likely dominated by surface structure (e.g., centimeter-scale roughness) rather than composition. The optimum incidence angle to detect CBOE would be near 45°, where neither the quasi-specular nor the diffuse backscatter components dominate the echo. This could be accomplished by an orbiting synthetic aperture radar that measures CPR and RCP and LCP for a range of incidence angles around 45°, with a resolution of 100 m or better. Such an experiment could distinguish ice from dry lunar surface by optimal viewing of all permanently shadowed regions. Such observations when combined with higher-resolution neutron spectrometer data would allow optimum targeting of in situ measurements to determine the detailed nature of lunar polar volatile deposits, thus conclusively determining the composition, origin, and areal distribution of the anomalies (ice?) identified at the lunar poles, allowing for the next steps of exploration and utilization by humans.

Appendix A

During processing the Clementine bistatic radar data set was sampled in discrete geographic bins (17 bins for orbit 234 and 10 bins for orbit 235). For completeness, the remaining sampling bins are presented in Plates A1 and A2 (see Plate 2 for orbit 234 bins 1–4 and orbit 235 bins 14–17).
Plate A2. Clementine bistatic radar targets (a) 1–4, (b) 5–8, (c) 9–12, and (d) 13 from orbit 234. Targets 14–17 are shown in Plate 2 (see overall location and explanation in Plate 1). On the response plots, the solid line represents CPR, and the top dashed line is LCP, while the bottom dashed line is RCP.
Plate A2. (continued)
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Acknowledgments. This manuscript benefited from useful discussions with W. Feldman, A. Binder, D. B. Campbell, N. J. S. Stacy, R. A. Simpson, G. H. Pettengill, I. J. Shapiro, R. Jurgens, and M. Slade. We thank N. J. S. Stacy for providing the Arecibo radar data. The Advanced Systems Office, NASA Johnson Space Center, under contract T-250W, supported this work. Additional support was furnished by the Naval Research Laboratory. This paper is Lunar and Planetary Institute contribution 99–1059.

References


