The Clementine Bistatic Radar Experiment

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During the Clementine 1 mission, a bistatic radar experiment measured the magnitude and polarization of the radar echo versus bistatic angle, \( \beta \), for selected lunar areas. Observations of the lunar south pole yield a same-sense polarization enhancement around \( \beta = 0 \). Analysis shows that the observed enhancement is localized to the permanently shadowed regions of the lunar south pole. Radar observations of periodically solar-illuminated lunar surfaces, including the north pole, yielded no such enhancement. A probable explanation for these differences is the presence of low-loss volume scatterers, such as water ice, in the permanently shadowed region at the south pole.

The possibility of ice on the moon was suggested in 1961 (1). Volatiles degassed from the primitive moon or deposited on the lunar surface by cometary and asteroidal impacts might migrate to and collect in permanently shadowed cold traps near the lunar poles, where they could be stable over geologic time (1–5). Because these cold traps receive no direct solar illumination, and emit little radiation, they are difficult to observe from the Earth. Radar can identify deposits of frozen volatiles because, under certain conditions, they produce a unique radar signature (6). However, such radar observations may not be conclusive depending on the quantity of volatiles present, the nature of the surface, and the sensitivity of the measurements. Frozen volatiles have much lower transmission loss than silicate rocks, producing a higher average radar reflectivity than silicate rocks. Total internal reflection also preserves the transmitted circular polarization sense in the scattered signal. An opposition surge or coherent backscatter opposition effect (CBOE) (7–12) may also be observed as the phase, or bistatic angle, \( \beta \) approaches 0. The CBOE requires scattering centers (cracks or inhomogeneities) imbedded in a low loss matrix such as ice (7–9). The preservation of the sense of polarization for CBOE has been observed in the laboratory using laser illumination of a particle suspension (13, 14). A high ratio of same sense to opposite sense polarization and high reflectivity has been detected by radar observations of the Galilean satellites of Jupiter (15, 16, 17), the residual south polar ice cap of Mars (18), portions of the Greenland ice sheet (19, 20), and the permanently shadowed polar craters of Mercury (21–23). These results are generally attributed to total internal reflection and/or CBOE produced by low loss frozen volatiles (6), although other mechanisms have been proposed (24). High-resolution ground-based synthetic aperture (monostatic) radar observations, from Arecibo, of the lunar south pole revealed some small anomalous same-sense polarization bright patches that are permanently shadowed (25). Brightening and enhancement of same sense polarization can be caused by double bounce reflections from large blocks or surface roughness. The presence of CBOE could distinguish brightening and polarization reversal produced by a low loss target from other scattering mechanisms. Bistatic radar measurements, using a spacecraft in orbit acting as the transmitter, can be used as a test for CBOE (13, 14, 20) by measuring the echo magnitude and polarization sense as a function of \( \beta \).

The Clementine 1 mission (26) provided data on the environment and geology of the polar regions of the moon (27, 28). In the northern hemisphere, no large basin overlaps the polar area. The south pole, however, is located within the South Pole-Aitken basin (SPA), an impact crater over 2500 km in diameter and averaging 12 km deep near the center of the basin (29). The pole is about 200 km inside the rim crest of Fig. 1. Orbital geometry of the Clementine bistatic radar experiment. The lunar polar tilt relative to the ecliptic (1.6°), the lunar tilt toward Earth (5°), and the bistatic angle \( \beta \) between spacecraft, lunar surface, and Earth receiver are shown.
the SPA. Because of its location inside this topographic low, the elevation of the south pole is likely to be several kilometers below the
mean lunar radius, resulting in zones of permanent shadow (27, 28). As the Clementine laser altimeter did not operate for
lunar latitudes greater than 70°, there is no altimetry data for the polar regions. However, multispectral images tend to preserve
concentric symmetry (30), thus the lunar south pole is estimated to lie about 5 to 8 km below the highest point of the basin rim
(29). If the elevation of the SPA rim crest on the near side is about 1 km, as suggested by the global map (31), then the pole would lie
at an elevation of about −4 to −7 km. Study of the illumination conditions near the south pole of the moon during the
mission revealed near constant illumination of several points within 30 km of the pole as well as darkness for other areas. Not all dark
regions observed by Clementine are permanently dark, as the images were obtained during southern winter, near the time when
the lunar spin axis obtained its maximum tilt away from the sun (1.6°). Initial analysis suggested that up to 3.000 km² near the
south pole was dark during the mission (27). Further analysis of the Clementine images of the south pole taken over a two-
month period revealed that some of this region was illuminated for a small portion (<12%) of the lunar month. Images of the
north pole taken on alternate orbits (10 hour intervals) during the first month and images of the south pole taken during the
second month were registered and added together to make composite images showing the extent of illuminated and darkened areas (Fig. 2). These composite images show the extent of darkness near the south pole is
much greater than that around the north pole. Mapping of the shadowed areas within a 2.5° latitude (75 km) radius circle of both poles reveals at least 6.941 km² of darkness around the south pole while only 5.36 km²
of darkness is measured around the north pole. A conservative analysis suggests an upper limit of 15,500 km² of south pole
terrain is likely to be in permanent darkness. As the cold trap area at the south pole is more extensive than at the north pole, it
would be expected (2) to retain more trapped volatiles.

In April 1994, during the times when the Earth passed through the Clementine orbital plane, the lunar axial tilt toward the
Earth as viewed from the NASA Deep Space Network (DSN) was relatively large (4.5° to 5.5°). This favorable alignment occurred once for each pole during the month. At these times the spacecraft, lunar target, and Earth-based receiver were co-
planar with the spacecraft orbital plane, and included the polar $\beta = 0$ condition (Fig. 1). Clementine transmitted an unmodulated S-
band (2.27 GHz, 1.35 cm wavelength) right circular polarization (RCP) signal with a net power of about 6 W through its
1.1 m high gain antenna (HGA), toward a specific lunar target. One of the DSN 70-m antennas served as a receiver. On 9 and 10
April 1994, bistatic radar observations were made of the south pole region during orbits 234, 235, 236, and 217. On 23 and 24 April
1994, observations of the north pole were conducted on orbits 299, 301, and 302. Analytical results for orbits 234, 235, 301,
and 302 are presented here. The other orbits had systematic errors originating in the spacecraft and the ground stations that
made the data unusable. Interpretation of the surface physical properties involved comparison of the measured echo compo-
ments with scattering models (32). In the initial analysis, the polarization ratio was compared to $\beta$ and local surface angle of

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**Fig. 2.** Composite Clementine orbital images of the poles of the moon, where more than 50 separate images have been summed together over one lunar day. In these views, areas of near permanent illumination are white and areas of near permanent darkness are black. Within 100 km of each pole, the south pole (B) shows considerable darkness (cold traps) whereas the immediate surroundings of the north pole (A) show at least an order of magnitude greater illumination, and are therefore warmer. The scale bar is 100 km.

**Fig. 3.** (A) Circular polarization ratio (RCP/LCP) as a function of $\beta$ for orbit 234 for a 2.5° radius latitude band centered on the lunar south pole and for orbit 235, for a 2.5° radius periodically illuminated band centered at 82.5° S, and for orbits 301 and 302, originating from a 2.5° radius band centered at the north pole. The area sampled is approximately 45,000 km² (orbits 234, 301, and 302) to 170,000 km² (orbit 235). (B) Individual polarization channel (RCP and LCP) echo power response used on a frequency bin-by-bin basis to compute the orbit 234 and 235 polarization ratios.
The scattering values presented represent regional averages. The normalized radar backscatter cross section (radar cross section per unit area) was estimated from the radar equation (34) and specific areas illuminated on the lunar surface. Typical values of normalized radar cross section derived from Clementine data for the moon's near-pole regions, $-80^\circ$S to $-82^\circ$S (84° angle of incidence, $\beta = \pm 1^\circ$), are $-29$ dB LCP (left circular polarization) and $-33.5$ dB RCP, consistent with previous work (25). During orbit 234 the $\beta = 0$ track (the locus of $\beta = 0$ points) and the center of the HGA beam were close within $0.5^\circ$ of each other and the south pole which provided for good illumination of the entire permanently shadowed south pole region at $\beta = 0$ condition. Orbit 235 has no $\beta = 0$ points near the south pole and is representative of periodically solar illuminated lunar surface. A noticeable peak in RCP/LCP occurs around $\beta = 0$ for the orbit 234 Doppler bins contained within a $2.5^\circ$ radius band centered on the lunar south pole (Figs. 3 and 4). Orbit 235 yielded no discernible enhancement in latitude bands that exclude the south pole region (Fig. 3). The peak in the RCP/LCP ratio observed in orbit 234 at $\beta = 0$, is due to enhanced power received in the RCP channel (Fig. 3) as opposed to a reduction in LCP, as seen at $\beta \sim 2.5$ to $3.0^\circ$. No statistically significant enhancement was observed in orbit 234 LCP (35).

During orbits 301 and 302 the spacecraft was roughly four times closer to the lunar north pole surface at $\beta = 0$ than during the south pole observations. The corresponding antenna pattern had a proportionally smaller footprint, and the incident power density was roughly an order of magnitude greater than for the south lunar pole. More sensitivity is therefore expected in detecting scattering enhancement. The north lunar pole observations showed no statistically significant polarization enhancements at $\beta = 0$ (Fig. 3). These observations were averaged over a latitude band of $2.5^\circ$ radius, centered on the north pole, containing an area comparable with the orbit 234 south pole observations. As the spacecraft velocity was greater near the north pole there are fewer $\beta = 0$ points in orbits 301 and 302. This produces flatter curves due to the filtering process (Fig. 3).

Clementine polar observations were conducted at incidence angles of 82° to 90°. High incidence angle scattering is difficult to predict and can exhibit unusual behavior due to shadowing, diffraction, and multiple scattering effects (36). However, no polarization ratio enhancement was observed on orbits 301 and 302, which had similar high incidence angle geometry and greater surface power illumination than orbits 234 and 235. Additionally, orbits 234, 235, 301, and 302 were re-analyzed, independently of $\beta$, to include only target areas at high local incidence angles (82° to 90°). Only orbit 234 showed an enhanced polarization ratio at high local incidence angles, which independently corresponds to south pole illumination at small $\beta$. All other orbits exhibited lower polarization ratio and no local angle of incidence dependent RCP/LCP enhancements. Statistical analysis (37) yields only a small probability ($\leqslant 5\%$) that the polarization ratio enhancement on orbit 234 is due to random variation in the data (Table 1), and it is probably not attributable to angle of incidence.

It is not certain whether the enhancement seen in orbit 234 is due to CBOE or some other scattering effect. The CBOE peak usually predicted from lossless volume scattering should be much narrower ($\leqslant 0.1^\circ$), and also show a larger enhancement in RCP and LCP, than was observed (7-12, 23). There are several possible explanations for these observations, including the possibility that they are not due to CBOE from ice deposits. The orbit 234 data have been averaged over a large area of lunar surface (45,000 km²) of which 14 to 33% is permanently shadowed (Fig. 4). If the putative ice deposits are small and patchy, the magnitude of the polarization reversal will be muted by reflections from the larger surrounding lunar surface area. Rocky lunar regolith may cover and be mixed with any ice deposits, further reducing the peak amplitude by increasing loss in the medium. Using the observed orbit 234 maximum, and median RCP/LCP ratios (Fig. 3 and Table 1), and methods used to estimate the extent of the Mercury polar deposits (23), we estimate the pure ice equivalent area of putative south pole ice deposits to be on the order of 0.2 to 0.3% of the observed region, or approximately 90 to 135 km². This area is consistent with small patches of high ($\geqslant 1$) RCP/LCP surface observed from Arcadia (25). The estimate may be a lower limit, as the viewing geometry does not let observation of the deepest parts of the shadowed terrain. The broad orbit 234 RCP/LCP peak and the low value of RCP/LCP (<1) are consistent with rigorous theoretical calculations of CBOE for measurements made at grazing incidence angles, assuming wavelength scale scatterers imbedded in a lossy medium (7-12). The observed orbit 234 RCP peak width and magnitude is predicted by CBOE theory if the scattering centers are nonspherical (11) and cover only a fraction of the sampled area. In this case the predicted LCP peak amplitude would be significantly smaller and its width much larger than the observed orbit 234 RCP peak (12), and is not observable in the Clementine data owing to the inherent fluctuation of the much larger LCP background. This does not preclude the existence of a number of small scattering areas with RCP/LCP > 1 and corresponding sharp RCP peaks that cannot be resolved in the data. These assumptions are geologically realistic for patchy, dirty ice. Other scattering mechanisms (roughness, double bounce) may explain the observed south pole RCP enhancement. However, the Clementine bistatic radar data only show this enhancement around $\beta = 0$ in an area at the lunar south pole containing at least 6361 km² of permanently shadowed ice.

![Fig. 4. Clementine mosaic of the south pole region of the moon showing area sampled on orbit 234.](image)

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<thead>
<tr>
<th>Orbit</th>
<th>RCP/LCP median value (dB)</th>
</tr>
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<tbody>
<tr>
<td>234</td>
<td>0.449 ± 0.019 (3.476 ± 0.178)</td>
</tr>
<tr>
<td>235</td>
<td>0.325 ± 0.031 (4.895 ± 0.151)</td>
</tr>
<tr>
<td>301</td>
<td>0.354 ± 0.014 (4.512 ± 0.171)</td>
</tr>
<tr>
<td>302</td>
<td>0.318 ± 0.012 (4.978 ± 0.166)</td>
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terrain. Clementine historic radar data taken from other, intermittently sunlit areas with similar geometry, and subjected to the same data reduction process, show no evidence of such an enhancement. This leads to the conclusion that the scattering mechanism responsible for the orbit 214 enhancement is associated with the permanently shadowed terrain, which is suggestive of a muted CROE originating from small patches of ice (and/or other frozen volatiles) covered and mixed with rocky material.

REFERENCES AND NOTES

30. Analysis was conducted using fast Fourier transform (FFT) techniques. The target area is isolated by Doppler shift, which makes bands of constant frequency to a set of lower ground locations (the j-o track). The ground points were close enough in distance to include all of the bands of constant frequency in the selected area. Repeat responses were filtered out. The analysis to extract radar scattering information from local regions on the surface were performed by sorting the Doppler data according to the parameter of interest. Typically frequency domain transform parameters were used to 1 to 3.4 points per noncoherent averaging, 1.496 to 1.5.386 points per FFT, a 1.991 Hann time data window, zero padding, and magnitude only (power) data stored in double precision output.