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FINAL REPORT

Surface Properties of the Moon, Venus and Small Bodies from Radar Observations

Type of Report:	SUMMARY OF RESEARCH
Principal Investigator:	Donald B. Campbell
Period Covered:	1 March 1994 - 31 August 1997
Institution:	Cornell University Ithaca, New York 14853
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SUMMARY

i) Lunar Studies

Studies of the moon during the period of the grant revolved around the issues of the possible presence of ice at the lunar poles and the determination of the electrical properties of the maria regoliths. The search for ice at the poles was conducted using measurements of the radar backscatter cross sections and circular polarization ratios measured from 125 m resolution Arecibo radar imagery at 13 cm wavelength obtained by Nicholas Stacy and the PI as part of Stacy's PH.D. thesis research. No clear indication of the presence of ice was found in areas thought to be in permanent shadow from solar radiation. However, a number of sub-kilometer-sized areas were found which have high backscatter cross sections and greater than unity polarization ratios, properties normally associated with the presence of ice. Some of these areas are sunlit in Clementine and Lunar Orbiter IV optical imagery and, hence, unlikely to have surface or near-surface ice. While a puzzle, these small, high-polarization areas tend to be associated with small impact craters and it is thought that their polarization properties are related to scattering from very rough areas on the crater's radar facing slopes. A paper reporting on these results was published in *Science* in June, 1997 (Stacy et al., 1997).

At the lunar poles, the earth-based radars are only slightly higher above the horizon than the limb of the sun so that there are large areas that are potentially in permanent shadow, and which might harbor ice deposits, that cannot be viewed by the radars. Given the rather chaotic terrain at the south pole, it is also very uncertain which areas are in permanent shadow during the entire eighteen-year lunar precessional cycle. In order to directly measure the topography at the lunar poles, Cornell graduate student Jean-Luc Margot and the PI have made interferometric SAR observations of the poles using the 70 m JPL/NASA Goldstone antenna to transmit and several nearby 34m antennas as the receive interferometer. Results from these observations, which are being processed under a new grant, will not only help to resolve the polar ice issue, they will also complement the lower latitude lunar topographic measurements from the Clementine spacecraft, almost completing the topographic map of the moon.

J-L. Margot, the PI and several collaborators used the Very Large Array to map the thermal emission of the moon in all four Stokes' Parameters at 90 cm, 21 cm and 6 cm wavelengths. The objective was to map changes in the regolith dielectric constant over a number of selected regions to infer composition and/or density changes, and to provide input to lunar radar scattering models derived by N. Stacy. Margot successfully carried out the very complex reduction of this data set, deriving dielectric constants over Mare Crisium, Sinus Iridum and several other areas. A paper is in preparation (Margot et al., 1997).

ii) The Icy Galilean Satellites

Then Cornell graduate student Greg Black modeled the radar backscattering behavior of the icy Galilean satellites using three wavelength measurements of their radar backscattering properties obtained with the Arecibo and Goldstone radars. This work formed part of Greg's Ph.D. thesis work and he defended his thesis (Black, 1997) in August, 1997. The radar scattering properties of Europa, Ganymede, and Callisto are unlike those of any other object observed with planetary radars. They are strongly backscattering with specific radar cross sections that can exceed unity. Polarization ratios are also high, ~ 1.5, indicative of multiple scattering, and the echos follow a diffuse scattering law at all incident angles with no indication of quasi-specular reflections. Observations made in 1988 and 1990 with the Arecibo radar at 70 cm wavelength were analyzed. The cross sections at this wavelength are much lower than previous results at wavelengths of 3.5 cm and 12.6 cm, although the polarization ratios are consistent. The unusual radar properties of these objects were modeled as a coherent backscatter effect which results from scatterers embedded in the weakly absorbing water ice surfaces of these moons. The model was applied to the observed wavelength variations of the radar properties to derive generalized properties of the scattering layer. This model can reproduce the data with scatterers following fairly steep power law size distributions with exponents of -3.5 to -4.0 and maximum sizes of 0.5 - 1.0 m. Efficient scatterers are required, and partially absorbing scatterers such as silicates cannot produce the high cross sections. The model is less sensitive to absorption in the scattering layer or its thickness, but suggests that the radar wave needs to penetrate only several tens of meters for this mechanism to produce the observed scattering properties. A draft of a paper for submission to *Icarus* has been completed (Black et al., 1997).

iii) Small Bodies

Most of our effort on small bodies went into developing and investigating methods for long baseline radar synthesis imaging of near-earth asteroids and comets. At X-band, the width of the synthesized beam of the Very Long Baseline Array (VLBA) is approximately 15 m at 0.03AU, a typical close approach distance for near-earth asteroids. At S-band, the resolution is about 60 m so that either the Goldstone 70 m antenna or the Arecibo 305 m antenna can be used to transmit at X- or S-band, respectively. Sensitivity issues may require that the VLBA be supplemented by a few larger antennas. Greg Black and the PI have submitted a separate grant application to develop the technique and to carry out test observations.

Mathew Class obtained a Cornell MS degree analyzing the rotation state of asteroid 4179 Toutatis using Arecibo radar observations (Class, 1995).

iv) Venus

A small amount of work was done analyzing Venus data from Arecibo and the Magellan mission. This work was done primarily in collaboration with Bruce Campbell of the Smithsonian and then Cornell undergraduate astronomy major, Chris DeVries. Most of the work revolved the comparison of the Arecibo measurements of the polarization properties of the highland regions with the emissivity and reflectivity measurements from Magellan. A paper reporting on this work has been sunmitted to *JGR Planets* (Campbell et al., 1997) and a review paper containing some of the work is in press (Pettengill et al., 1997).

THESES AND PAPERS PUBLISHED, IN PRESS, OR IN PREPARATION:

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"The Rotation State of Asteroid 4179 Toutatis", M.A.Class, MS Thesis, Cornell University, 1997.

"Chaotic Rotation of Hyperion and Modeling the Radar Properties of the Icy Galilean Satellites as a Coherent Backscatter Effect", G.J.Black, Ph.D. Thesis, Cornell University, 1997.

"Arecibo Radar Mapping of the Lunar Poles: A Search for Ice Deposits", N.J.S. Stacy, D.B. Campbell, and P.G. Ford, *Science*, 276, 1527-1530, 1997.

"Surface Electromagnetic Properties", G.H. Pettengill, B.A. Campbell, D.B. Campbell, and R.A. Simpson, Chapter 4C in Venus II, in press, 1997.

"Surface Processes in the Venus Highlands: Results from Analysis of Magellan and Arecibo Data", B.A Campbell, D.B. Campbell, and C.H. DeVries, submitted to *JGR-Planets*, July (1997)

"Icy Galilean Satellites: 70 cm Radar Results and the Coherent Backscatter Effect", G.J. Black, D.B. Campbell, and P.D. Nicholson, in final draft.

"Electrical Properties of the Lunar Surface from Radio Thermal Observations", J-L., Margot, D.B. Campbell, B.A. Campbell, and B. Butler, in preparation.

ABSTRACTS

OF

CONFERENCE PRESENTATIONS

Abstract presented at the 29th annual meeting of the Division for Planetary Sciences, Jul 1997 in Cambridge, MA.

High Resolution Topographic Maps of the Lunar South Pole.

J. L. Margot[1], D. B. Campbell[1], R. F. Jurgens[2], M. A. Slade[2], N. J. Stacy[3], [1]Department of Astronomy and Space Sciences, Cornell University, [2]JPL/Caltech, [3]DSTO, Australia.

Topographic maps of the South Polar region of the Moon are derived from new high resolution ground-based radar maps. The images were obtained with the Goldstone X-band system ($\lambda = 3.5$ cm) using the 70 m antenna to transmit and two 34 m antennas to form a receive interferometer. In this interferometric mode, heights above a reference surface can be derived from the relative phase between the two radar signals [1]. A focused delay-Doppler technique [2] is used to generate backscatter maps with a surface resolution of 75 m. The combination of the complex reflectivities is expected to yield surface heights at a similar resolution.

Current map coverage includes an area ~450 km in range by ~300 km in Doppler, with latitudes ranging from -80 degrees on the near side to -85 degrees on the far side. Future observations are planned to map two regions of similar extent to the East and West of the South Pole, as well as the North Polar area.

The topographic maps will be used to estimate solar illumination around the poles, taking the 18.6 year lunar precessional cycle into account. This effort is motivated by an attempt to identify areas of permanent shadow, and may provide a valuable tool in evaluating the likelihood of the presence of volatiles on the Moon. The topographic data will also be useful in complementing Clementine's altimetry and extending its coverage into the polar regions [3].

As one of the two receiving antennas had dual polarization capability, new circular polarization ratio maps of the South Pole can be derived. These will complement similar maps obtained at Arecibo at 12.6 cm [4] and refine the search for unusual polarization signatures that may be indicative of ice

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[2] N. J. Stacy (1993). Ph.D Thesis, Cornell University.
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Abstract presented at 29th Annual Meeting of the Division of Planetary Sciences, July 1997 in Cambridge, MA.

Icy Galilean Satellites: Radar Echoes due to a Coherent Backscatter Effect

G. J. Black, D. B. Campbell, P. D. Nicholson, Cornell University

We have modeled the radar scattering properties of Europa, Ganymede, and Callisto using a vector formulation of the coherent backscatter effect [1]. At wavelengths of 3.5 cm and 12.6 cm, the specific radar cross sections [2] of the icy Galilean satellites are not only an order of magnitude larger than those of typical inner Solar System targets, but also greater than unity, indicating that these icy surfaces preferentially backscatter. Even more unusual is that the icy surface reflection mechanism largely preserves the incident polarization. At 70 cm wavelength the cross sections of Europa, Ganymede, and Callisto are lower than those measured at the shorter wavelengths by factors of 4-10, while the polarization ratios appear to remain at high values [3].

In order to explain the radar data several possible mechanisms have been proposed by various workers, all of which are based on the fact that the surfaces and upper layers of these moons are mainly water ice. Water ice at the low temperatures found on these objects is a poor absorber of radio-wavelength radiation, permitting the radar signal to penetrate more efficiently into the surface than is possible with silicate compositions. We have adapted a model of the coherent backscatter effect [1] to explain the observed wavelength dependence of the radar cross sections. Since the subsurface attenuation coefficient can be quite small, the presence of embedded wavelength-scale scatterers may result in this particular multiple-scattering process, thus enhancing the echo near exact backscatter as well as preserving the incident polarization. By assuming Mie scatterers that are distributed in size as a power law, we fit the observed wavelength variations in cross section and polarization properties. Model parameters that best reproduce the data indicate that the scattering layers are on the order of ten meters thick. The scatterer size distributions follow fairly steep power laws, with the maximum scatterer sizes falling between the two longest wavelengths. The absorption lengths in the media are not well constrained but must be longer than the depth of the respective layer.

[1] Peters, K. (1992). *Phys. Rev. B* **46**, 801. [2] Ostro, S. J., *et al.* (1992). *JGR* **97**, 18227. [3] Black, G J., *et al.* (1996). *LPSC* XXVII **1**, 143.

Abstract presented at the Workshop on Remote Sensing of Planetary Ices: Earth and other Solid Bodies, June 1997 in Flagstaff, AZ.

Modeling the Radar Scattering Properties of the Icy Galilean Satellites

G. J. Black, D. B. Campbell, and P. D. Nicholson (Cornell University)

It has been known for over 20 years that the large icy moons of Jupiter; Europa, Ganymede, and Callisto, have radar scattering properties unlike any other radar detected Solar System object. At wavelengths of 3.5cm and 12.6cm, the radar cross sections of the icy Galilean satellites are an order of magnitude larger than those of typical inner Solar System targets such as the terrestrial planets, the Moon, and most asteroids. These extremely high cross sections indicate that the surfaces preferentially backscatter the incident power. When a circularly polarized signal is transmitted, inner Solar System objects tend to return most power in the oppositely polarized sense as would be expected to result from single surface reflections. Typically only 10% of the echo power is returned in the same circular polarization, and is generally due to wavelength-scale surface roughness. For Europa, Ganymede, and Callisto the case is quite different. In addition to their large cross sections, more power is returned in the same circular sense than in the opposite circular sense, contrary to the result expected for single surface reflections. This inversion of the circular polarization indicates that single scattering events from the vacuum-surface interface are not contributing significantly to the echo, and another process must be driving the large cross sections There is little variation in radar properties between the wavelengths of 3.5cm and 12.6cm [1]. At 70cm the cross sections fall by almost an order of magnitude, while the polarization ratios appear to remain at their high values [2]. This indicates that the same mechanism is operating at the much larger wavelength, but not nearly as effectively.

In order to explain the radar data several possible mechanisms have been proposed by various workers, all of which are based on the fact that the surfaces and upper layers of these moons are mainly water ice. Water ice at the low temperatures found on these objects is a poor absorber of radio-wavelength radiation. This permits the signal to penetrate much deeper below the surface than is possible on silicate surfaces. Multiple subsurface scattering processes may then contribute significantly to the returned power We have adapted a model of the coherent backscatter effect [3] to explain the observed wavelength dependence of the radar cross sections. This effect arises from coherent interference of photons following similar subsurface scattering paths but in opposite directions, thereby boosting the echo near exact backscatter, as well as preserving the incident polarization. By assuming the scatterers to be Mie scatterers that are distributed in size as a power law, we fit the observed wavelength variations in cross section and polarization properties. Model parameters that best reproduce the data indicate that the scattering layer is on the order of ten meters thick. The scatterer size distribution follows a fairly steep power law, with the maximum scatterer size falling between the two longest wavelengths, 12.6cm and 70cm. The cutoff in the distribution at this size is required by the drop in cross section at 70cm; there must be significantly fewer wavelength-sized scatterers at 70cm than at the shorter two wavelengths. The absorption length in the medium is not well constrained but must be longer than the depth of the layer.

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A Radar Search for Ice Deposits at the Lunar Poles

D. B. Campbell (Cornell University) and N. J. S. Stacy (DSTO, Adelaide, Australia)

The Arecibo 12.6 cm wavelength radar was used to image the polar regions of the moon at a resolution of approximately 125m in a search for ice deposits in areas of possible permanent shadow from the sun. A circularly polarized wave was transmitted with the Arecibo 305m antenna and echoes in both senses of circular polarization were received using a 30m antenna located 11km from the 305m antenna. For the observations of the north pole in May, 1992 the Arecibo Observatory was 4.1^0 above the horizon while for the south pole observations the Observatory was 6.1^0 above the horizon, close to the maximum. Given the 1.53^0 inclination of the moon's equatorial plane to the ecliptic plane, the limb of the sun can be up to 1.82^0 above the horizon. The small angle differences mean that, depending on the unknown lunar topography at the poles, some but by no means all, of the areas shadowed from the sun could be observed with the Arecibo radar system.

No large, multi-km^2 areas were found with high radar backscatter cross sections and high circular polarization ratios, properties suggestive of the presence of ice. A number of sub-km^2 areas have these properties but optical images from the Clementine and Lunar Orbiter IV missions show some of these features to be in sunlight. Small features with similar properties were also found in Arecibo radar images of Sinus Iridum on the northern edge of Mare Imbrium at about 47^0 N latitude. The coincidence of some of these features with the radar facing slopes of craters and their presence in sunlit areas suggests that very rough surfaces rather than ice deposits are responsible for their unusual radar properties.

The Arecibo and Clementine bistatic radar experiments were similar in that they both used a 2.4GHz radar system and measured the scattered circular polarization signal. While the transmitter positions were different, both used a ground based receiving antenna so the area viewed was constrained by the earth-moon geometry. The Arecibo observations of the south pole region made with the Arecibo telescope 6.1^0 above the horizon imaged fractionally more features near the pole than the Clementine experiment where the receiving antenna was 4.5^0 to 5.5^0 above the horizon. The Clementine experiment measured the radar cross sections averaged over a large area as a function of the bistatic angle while the Arecibo experiment measured just the backscatter cross sections at high spatial resolution. The Arecibo data was averaged over our best estimates of the Clementine footprints at the south pole, the north pole and the reference area near the south pole for comparison with the Clementine circular polarization ratio (CPR) measurements. The Arecibo data gave much more uniform CPR values for the three areas than reported in (1) for the Clementine experiment; 0,51 vs 0.45 for the south pole, 0.50 vs 0.35 for the north pole and 0.43 vs 0.29 for the south pole reference area.

LUNAR DIELECTRIC CONSTANTS FROM APERTURE SYNTHESIS POLARIMETRY AT 6 CM.

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Measurements of the Moon's polarized thermal radio emission at 6 cm were obtained with the Very Large Array (VLA). The polarization properties of the emission are determined primarily by the dielectric constant of the regolith material, the fraction of the emergent radiation that is diffused, and the surface roughness on scales larger than the wavelength. Maps of all Stokes parameters were used to provide estimates of the regolith dielectric constant at ~25 km resolution. The values for a smooth Moon range from ~1.6 to ~2.5, with an average of ~2.0. These values are lower than those derived from similar emission measurements at 21 cm [1] ($\epsilon \simeq 2.7$) and from earlier radar estimates ($\epsilon \geq 2.5$). Results are illustrated for the Crisium and Sinus Iridum areas where some mare regions have dielectric constants ~2.1 and highland regions have values of ~1.9 These variations cannot be accounted for by large scale roughness alone.

The observations were performed with the VLA[1] in its most compact (D) configuration on April 12, 1995 Eight hours of observation were used to cycle through four different sites. The array resolution at the center of the lunar disk was 14", or 25 km, and the diameter of each area imaged was 8', or roughly 1000 km. Stokes parameters were formed by combining measurements in two circular polarizations.

Because the interferometer did not sample critical low spatial frequency components, traditional deconvolution algorithms failed to properly remove the array sidelobe response and to improve image quality Image restoration was achieved by fitting models of the emission in each Stokes parameter to the visibility function, thereby providing the low spatial frequency components unseen by the interferometer These model components were then combined with the high resolution data to form images.

Deconvolved images of the Stokes parameters were used to compute the degree of linear polarization of the Lunar thermal emission, which in turn provides estimates of the dielectric constant. The inversion method was outlined in Margot et al. [1] and relies on differences between the transmission coefficients parallel and perpendicular to the plane of emission at the regolith-vacuum interface. This technique is independent of absolute calibration and is limited to high emission angles. It is fairly insensitive to the loss tangent of the material, and therefore more diagnostic of bulk density than oxide content.

Results of the fits for the four areas observed are illustrated in table 1, and variations at each site are roughly ±0.2 about the indicated average value. (The fits at the last site yield a temperature value higher than expected which, if in error, would result in a slight underestimate of ϵ). Dielectric constant

Site	Lat	Lon	ϵ_{avg}
S. Iridum	39.5	-32.5	2.1
Tycho	-47.0	-11.3	2.0
Plato	55.0	-9.7	2.2
Crisium	17.4	29.0	1.9

Table 1: Average dielectric constants obtained at the observed sites by fitting the visibility function.

values centered around 2.0 are in agreement with previous radio polarimetric studies at 6 cm [2], but contrast with typical radar estimates of the dielectric constant (≥ 2.5) at comparable wavelengths [3] [4]. Diffusion by wavelength-scale structure at the surface lowers radio estimates of the dielectric constants and partially explains the discrepancy.

The observed values of the dielectric constant at 6 cm also contrast with an average value of 2.7 obtained at 21 cm using the same technique [1] In an attempt to explain the discrepancy, radiative transfer modeling was performed on various density profiles of the upper regolith. These simulations showed that the measured values of the dielectric constant are characteristic of the very top layer of the regolith (depth $\lambda/10$ or less), unless sharp density increases are present. No realistic density profile of the upper meter of the regolith could reproduce both values inferred at wavelengths of 6 cm and 21 cm, even when very abrupt density profiles were considered. A layer of bedrock with higher dielectric constant ($\epsilon = 6.5$) better explains the observed values at the two wavelengths, but only if placed very close to the surface (~1 meter).

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[1]The VLA is a facility of the National Radio Astronomy Observatory which is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation

Maps of the dielectric constant around Crisium and Sinus Iridum are shown in figures 1 (a) and 2 (a) respectively. Arecibo 70 cm radar backscatter maps [5] of the same regions are provided for comparison. As observed previously at 21 cm [1], some mare units display higher dielectric constants than the surrounding highlands, and the difference cannot be accounted for by large scale roughness effects alone. Typical variations at Sinus Iridum are 1.9 to 2.3 at 6 cm, while the values measured at 21 cm ranged from 2.4 to 3.0. If interpreted in terms of bulk density at the regolith interface, the highland and mare regions would have a density of ~1.0 gcm^{-3} and 1.2 gcm^{-3} respectively, in contrast with higher estimates at 21 cm wavelength [1].

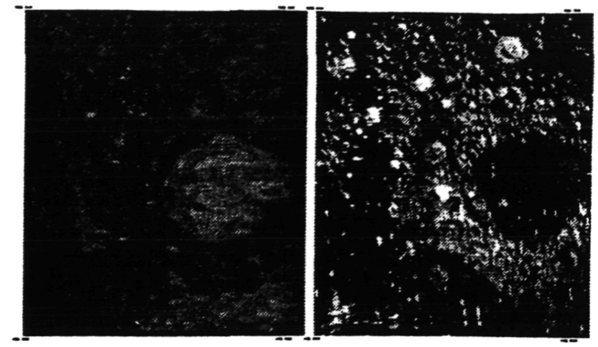

Figure 1: (a) Dielectric constant map of the Mare Crisium area obtained from thermal emission measurements at 6 cm. Values range from 1.8 to 2.1. The map includes selenographic latitudes from -3° to 40°, and longitudes from 24° to 70° East. (b) Arecibo radar map of the same region at 70 cm.

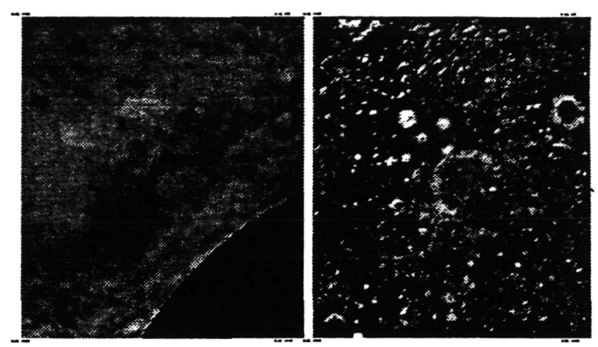

Figure 2: (a) Dielectric constant map of the Sinus Iridum area obtained from thermal emission measurements at 6 cm. Values range from 1.9 to 2.3. The map includes selenographic latitudes from 23° to 63°, and longitudes from 0° to 72° West. The blanked region corresponds to emission angles lower than 35°, where the inversion is unreliable. (b) Arecibo radar map of the same region at 70 cm.

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Abstract presented at 28th Annual Meeting of the Division of Planetary Sciences, October 1996 in Tucson, AZ.

The Icy Galilean Satellites: Modeling Surface Properties from Multi-wavelength Radar Measurements

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The radar properties of the icy Galilean satellites at cm wavelengths are dramatically different from those of most inner solar system objects. Data obtained with the Goldstone and Arecibo systems at wavelengths of 3.5cm and 13cm yield total radar cross sections for Europa, Ganymede, and Callisto of ~ 2.5, ~ 1.5 and ~ 0.7 respectively, and circular polarization ratios in the range $1.2-1.5$ [Ostro *et al.* *JGR* **97**, 18227 (1992)]. However, Arecibo measurements made at 70cm wavelength yield cross sections substantially lower, while the circular polarization ratios are generally consistent with the 3.5cm and 13cm wavelength values [Black *et al.* *LPSC XXVII* **1**, 143 (1996)].

The radar scattering properties of Europa, Ganymede, and Callisto are thought to be due to the low absorption of cm wavelength radiation in ice. A low-loss medium permits long path lengths, allowing volume scattering from subsurface structures. Hapke [*Icarus* **88**, 407 (1990)] first suggested that a coherent backscatter effect can explain the radar observations. This effect results in an enhanced backscatter cross section and a greater than unity circular polarization ratio; i.e. the incident sense of polarization is largely preserved in the backscatter direction.

We fit a model of the coherent backscatter effect from Peters [*Phys. Rev. B* **46**, 801 (1992)] to the measured cross sections at the three different wavelengths for each object in order to constrain surface properties. The model parameterizes the scatterers in terms of a power law size distribution and a mean angle for individual scattering events. The medium containing the scatterers is parameterized by an absorption path length and thickness. Preliminary results indicate that the scatterer size distribution can be described by a power law (number density of scatterers with a given radius $n(r) \propto r^{-\alpha}$) with α falling in the range $2-3$, and that the scattering layer may be extremely thin, on the order of a few meters. Absorption in the medium is not well constrained by the model.

Abstract presented at the 27th Lunar and Planetary Science Conference, March 1996 in Houston, TX.

THE ICY GALILEAN SATELLITES: 70cm WAVELENGTH RADAR PROPERTIES; G. J. Black, D. B. Campbell, Space Sciences Bldg, Cornell University, Ithaca, NY 14853; S. J. Ostro, JPL/Caltech, Pasadena, CA 91109.

The radar properties of the icy Galilean satellites at cm wavelengths are dramatically different from those of most inner solar system objects. For the terrestrial planets, the Moon, and most smaller objects, specific radar cross sections are typically on the order of 0.1 while circular polarization ratios, defined to be the ratio of the echo power received in the same circular sense (SC) as transmitted to that received in the opposite sense (OC), range from $\sim$ 0.1 to 0.4. As shown in Table I, at wavelengths of 3.5cm and 13cm, total radar albedos for Europa, Ganymede, and Callisto, are $\sim$2.5, $\sim$ 1.5, and $\sim$ 0.7 respectively, and circular polarization ratios lie in the range $\sim 1.2 - 1.5$ [1]. In addition, reflections from terrestrial planets include specular reflection from near the sub-radar point. No such specular return is seen in the echoes from the icy Galilean satellites; the scattering closely follows a diffuse $\cos^n\theta$ law at all incident angles, with $n \sim 1.6$ [1]. These measurements show no significant variation with wavelength from 3.5cm to 13cm. Here we report on the reduction of measurements made at a much longer wavelength, 70cm, in 1988 with the Arecibo telescope. Observations were made on 7 days, one day on Europa and three each on Ganymede and Callisto, with $\sim$ 1 hour of integration time on each day. Single-day signal-to-noise ratios were very small and all three days were averaged to obtain significant detections of Ganymede and Callisto. Even so, Callisto was not detected in the OC channel. Europa was not detected in either circular polarization on the single day in which it was observed. Good detections of Ganymede were obtained in both channels.

The measured mean cross sections, $\hat{\sigma}$, and circular polarization ratios, μ_C, for the 70cm observations are given in Table I. The most surprising result is that the 70cm cross sections are substantially lower than those for the shorter wavelengths. Since there was no clear detection of Europa in either channel, only an upper limit on both cross sections at three standard deviations of the noise are given. These upper limits are an order of magnitude lower than the cross sections at 3.5cm and 13cm wavelengths. For Ganymede, the cross sections are lower than at the shorter wavelengths by a factor of $\sim$ 4 in each polarization. Finally, Callisto also shows a low 70cm cross section with no detection in the OC channel and only a marginal detection in the SC. The OC cross section is the upper limit at three standard deviations of the noise, and is an order of magnitude lower than the 3.5cm and 13cm wavelength cross sections.

The circular polarization ratio for Ganymede is consistent with the ratios at shorter wavelengths. The detection of Callisto in only the SC channel allows the possibility that the circular polarization ratio is much larger at 70cm. Given only upper limits for both cross sections, no polarization ratio could be calculated for Europa.

The unusual radar properties of the icy Galilean satellites are thought to be due to the low absorption of cm wavelength radiation in ice. This low loss medium allows long path lengths, resulting in volume scattering from subsurface structures. A coherent backscatter effect arising from subsurface multiple scatterings may explain the radar data. First applied to this problem by Hapke [2], this effect greatly enhances the fraction of radiation backscattered and gives large polarization ratios; i.e. the incident sense of polarization is largely preserved (see [3] and [4]).

Current work is aimed at determining if any observed wavelength dependence (or independence) can place constraints on the sizes, separation, or composition of these scatterers. The lower cross sections at 70cm relative to those measured at 3.5cm and 13cm wavelengths may be indicative of a change in the distribution or properties of the scatterers between those wavelengths. For example, density heterogeneities may be relatively uncommon at larger scales.

Long wavelength data has the potential to improve our understanding of the wavelength dependence of the icy Galilean satellites' radar scattering properties. Additional 70cm data was taken in 1990, and is currently being reduced. Beginning in 1999 when Jupiter is again observable from Arecibo, additional 70cm (and 13cm) data will be obtainable.

References:

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[4] Peters K. (1992) *Phys. Rev. B*, **46**, 801.

Table I†

Target	λ(cm)	$\hat{\sigma}_{OC}$	$\hat{\sigma}_{SC}$	μ_C
Europa	3.5	0.91 ±0.13	1.40 ±0.13	1.43 ±0.24
Europa	13	1.03 ±0.08	1.58 ±0.14	1.53 ±0.03
Europa	70	<0.14*	<0.12*	
Ganymede	3.5	0.65 ±0.10	0.90 ±0.10	1.40 ±0.10
Ganymede	13	0.57 ±0.06	0.82 ±0.09	1.43 ±0.06
Ganymede	70	0.16 ±0.06	0.24 ±0.04	1.50 ±0.61
Callisto	3.5	0.32 ±0.02	0.40 ±0.04	1.22 ±0.08
Callisto	13	0.32 ±0.03	0.37 ±0.03	1.17 ±0.04
Callisto	70	<0.03*	0.12 ±0.08	>1.33

†3.5 and 13 cm results are from [1].

* values represent three standard deviations of the noise

LUNAR DIELECTRIC CONSTANTS FROM RADIO THERMAL EMISSION MEASUREMENTS; J.L. Margot[1], D.B. Campbell[1], B.A. Campbell[2], and B.J. Butler[3], [1]Department of Astronomy and Space Sciences, Cornell University, Space Sciences Building, Ithaca, NY 14853, [2]Center for Earth & Planetary Studies, National Air & Space Museum, Washington, DC, 20560, [3]National Radio Astronomy Observatory, P.O. Box 0, Socorro, NM 87801.

Thermal emission from the Moon at 21 cm was measured in all four Stokes parameters with the Very Large Array (VLA). The polarization properties of the emission are determined primarily by the dielectric constant of the regolith material, the fraction of the emergent radiation that is diffused, and the surface roughness on scales larger than the wavelength. Estimates of the dielectric constant were obtained at ~90 km resolution and the smooth sphere values range from ~2 to ~4. Results are illustrated for the Crisium area where the mare regions have dielectric constants ~2.7 and highland regions have values of ~2.4. A map of the dielectric constant shows that the various regions correlate well with 70 cm radar data. Using a facet model, it is shown that the observed variations around Crisium cannot be accounted for by roughness at very large scales. Previous estimates of lunar rms surface slope are used to provide absolute measurements of the dielectric constant. For negligible diffusion of the emission by wavelength-scale structure at the surface, the values of the dielectric constant corrected for roughness are ~2.7 for Mare Crisium and ~2.5 for the surrounding highlands. These variations could be explained by near-surface density changes (mare density ~1.52 gcm^{-3}, highlands density ~1.41 gcm^{-3}), where the dichotomy is consistent with heavier basaltic materials dominating the mare regolith.

The observations were performed with the VLA[1] in its most compact (D) configuration on April 12–13, 1995. A single 6 hour observation was sufficient to provide adequate sampling of the visibility function. At a wavelength of 21 cm, the synthesized resolution is 50", or ~90 km at the center of the lunar disk. Emission was measured in two circular polarizations from which the Stokes parameters were derived. Deconvolution of the data was performed in each Stokes parameter using the Clean algorithm. The cleaning process was started with an initial guess based on the expected polarization response from a smooth dielectric sphere. Residual rms temperature noise values are 1.7 K, 0.3 K, and 0.4 K in the I, Q, and U Stokes parameters respectively.

Estimates of the dielectric constant can be obtained due to differences in the thermal emission parallel and perpendicular to the plane of emission at the regolith-vacuum interface. For a smooth surface with dielectric constant ϵ and zero conductivity, the ratio of brightness temperatures is [1]

$$\frac{T_{\|}}{T_{\perp}} = \frac{\epsilon(\cos\theta + \sqrt{\epsilon - \sin^2\theta})^2}{(\epsilon\cos\theta + \sqrt{\epsilon - \sin^2\theta})^2}, \tag{1}$$

where θ is the emission angle. This ratio can be related to the degree of linear polarization $m = (Q^2 + U^2)^{1/2}/I$. Images of the I, Q and U Stokes parameters are used to compute these quantities on a pixel by pixel basis, and equation (1) is inverted numerically.

A map of the dielectric constant around Mare Crisium is shown in figure 1 (a). These values are not corrected for large-scale roughness or surface diffusion of the emergent radiation. Figure 1 (b) is an Arecibo 70 cm radar backscatter map of the same region [2]. Comparison of the two figures reveals that the mare units display higher dielectric constants than the surrounding highlands. As shown by the histogram on figure 1 (c), a typical range of values for the Crisium area highlands is $\epsilon = 2.4$, with $\epsilon = 2.7$ for the mare regions. A facet model similar to that used by Golden [3] and Arvidson et al. [4] demonstrates that such a change cannot be accommodated by large-scale

[1]The VLA is a facility of the National Radio Astronomy Observatory which is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.

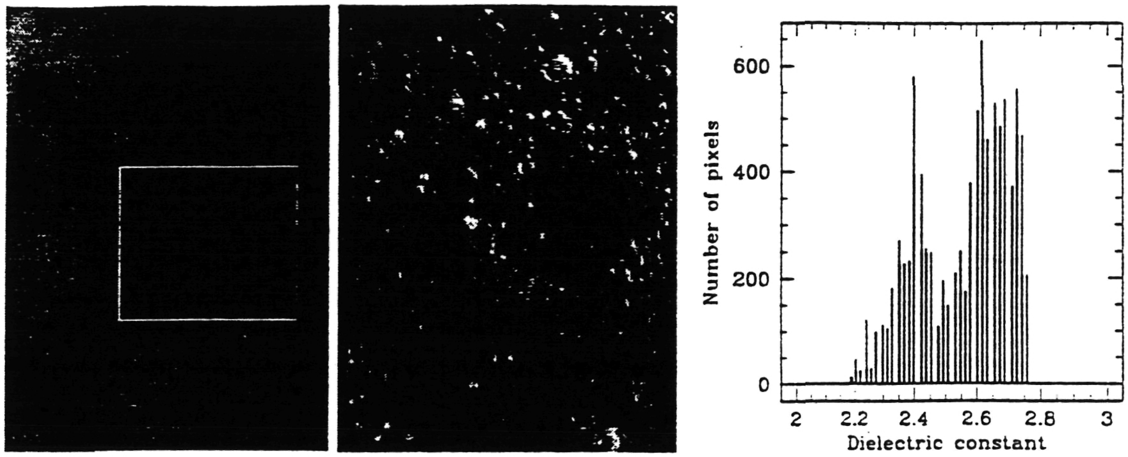

Figure 1: (a) Dielectric constant map in orthographic projection of the Mare Crisium area obtained from thermal emission at 21 cm. Selenographic latitudes are from -10° to 42°, longitudes are from 30° to 70° East. Emission angles vary from 50° to 70°. Mare Fecunditatis is seen at the bottom of the image and the edge of Mare Tranquillitatis is seen at the left. (b) Arecibo radar backscatter map of the same region at 70 cm. (c) Histogram of dielectric constant values from the rectangular area in (a).

roughness variations for reasonable values of lunar rms surface slope. Previous estimates of the rms surface slope in highland regions indicate values of 8° [5] to 10° [6]. Assuming negligible diffusion of the emergent radiation by wavelength-scale structure, the values of the dielectric constant corrected for rms slope variations are ~2.7 for Mare Crisium and ~2.5 for the surrounding highlands. A contribution from diffuse emission at the boundary would tend to raise both of these values. Using a relationship between dielectric constant and density [7], these measurements yield densities of ~1.52 gcm^{-3} and ~1.41 gcm^{-3} respectively. This change is consistent with the greater density of the basalts which make up the mare regolith, in contrast to the lighter materials which comprise the highlands.

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A SEARCH FOR ICE AT THE LUNAR POLES; N.J.S. Stacy, Defence Science and Technology Organisation, Salisbury, South Australia, Australia and D.B. Campbell, National Astronomy and Ionosphere Center, Cornell University, Ithaca, NY 14853.

Discovery of probable water ice deposits on permanently shadowed crater floors near the poles of Mercury [1,2] suggested the possibility of similar deposits near the lunar poles. The interpretation that ice is responsible for the anomalous radar echoes discovered with the Goldstone and Arecibo radar systems, rests primarily on the unusual radar backscatter properties of many icy surfaces in the solar system, high backscatter cross section and greater than unity circular polarization ratio. While ice, with a dielectric constant of 3.15, does not have an intrinsically high reflectivity, it has low loss and so may serve as a weakly absorbing material which could support volume scattering mechanisms such as the coherent backscatter opposition effect [3].

For earth based telescopes, the geometry for observations of the lunar poles is less favorable than for Mercury. As viewed from the lunar poles, the Arecibo observatory rises a maximum of about 6 deg above the horizon while, given the 1.5 deg inclination of the moon's equatorial plane to the ecliptic plane, the limb of the sun can be up to 2 deg above the horizon. This small difference means that a significant percentage of the area shadowed from the sun is also shadowed from the radar and, hence, not observable.

Radar images were obtained of the north and south polar regions of the moon in May and August of 1992 with the Arecibo 12.6 cm wavelength radar. A circularly polarized wave was transmitted and images formed in both senses of received circular polarization. The 4 look images have resolutions of approximately 150m and cover areas of approximately 400km x 400km. Figure 1 shows a 4x4 averaged image of the south pole in the expected sense of circular polarization (the polarization expected from a single mirror like reflection). The polarization ratio is the ratio of the backscatter cross section in the opposite (cross polarized) sense to that in the expected sense.

An examination of the images revealed no large area of high backscatter cross section and polarization ratio greater than unity, and no systematic association of such properties with impact craters. However, there are a number of isolated areas, especially near the south pole, which have high cross sections and polarization ratios near unity. Most of these are coincident with the radar facing inner walls of craters and are probably due to enhanced wavelength scale surface roughness. Similar behavior is observed for craters in other areas of the moon which are clearly not in permanent shadow. One small crater near the south pole, which may be in permanent shadow, has a radar facing inner wall with high cross section and a polarization ratio of about 2.5. If the high ratio is due to ice deposits, it is not clear why it would be associated with the radar facing inner wall. One possibility is that ice excavated by the impact is causing an enhancement of the polarization ratio. However, geometric effects, such as a double bounce from the crater floor, may also be responsible.

While there are a number of features at the lunar poles which warrent further study, there is no clear evidence from the Arecibo images for the presence of ice. Because of the difficult geometry for earth based observations, a complete search should be done from an orbiting spacecraft. Such a mission could also measure the topography in the polar regions to determine which areas may have been in permanent shadow for a significant fraction of the moon's age.

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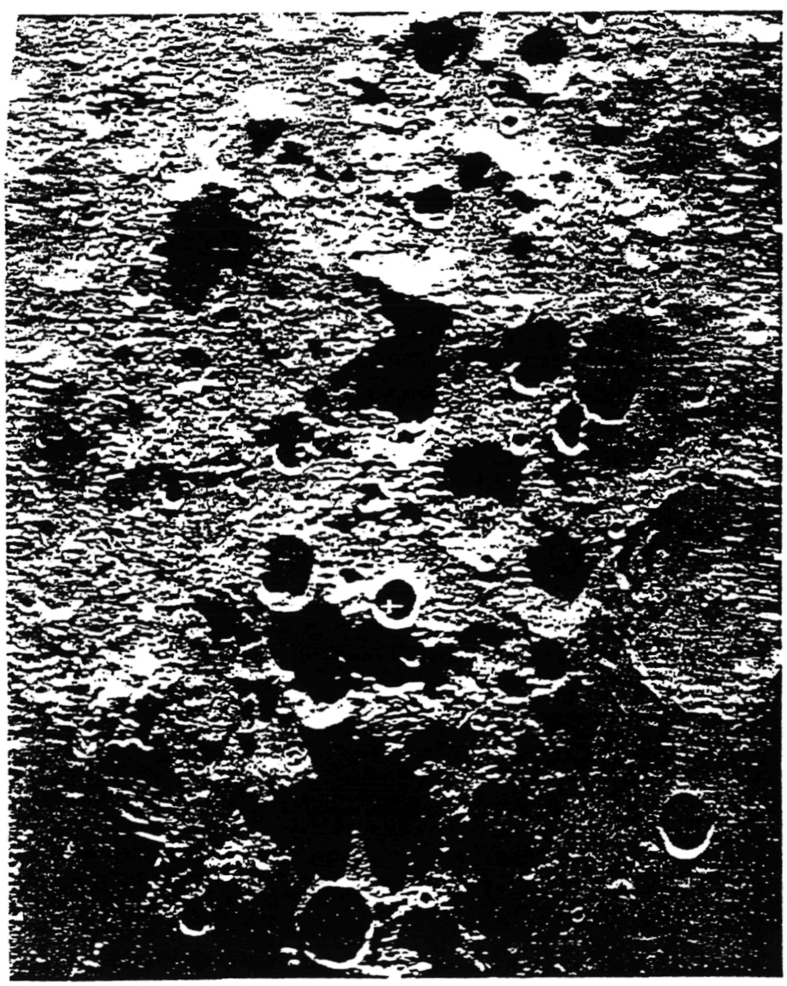

Figure 1. A delay-Doppler image of the south pole of the moon.