RADAR STUDIES OF THE LUNAR REGOLITH: Bruce A. Campbell, *Center for Earth & Planetary Studies, Nat. Air & Space Museum*; B. Ray Hawke, *University of Hawaii;* T.W. Thompson, *Jet Propulsion Laboratory.*

Recent acquisition of Clementine multi-spectral data for the Moon have rekindled long-standing questions on the composition, vertical structure, and mechanical properties of the lunar regolith. Long-wavelength imaging radar data can be used to probe 10 m or more below the surface to address these issues, and we report here on continued analysis of the 70-cm measurements of Thompson [1]. These data have been "calibrated" to values of backscatter coefficient by reference to previous full-disk lunar studies, which permits a direct comparison between lunar targets and relevant terrestrial AIRSAR observations at the same wavelength. We have focused on comparisons between the 70-cm radar echoes and maps of Fe and Ti abundance derived from earth-based telescopic data and Apollo orbital geochemistry experiments, and on analysis of the likely scattering mechanisms within the regolith. This work shows that: (1) there is no systematic correlation between radar backscatter from the lunar maria and multi-spectral estimates of TiO_2 abundance; (2) there is likewise no systematic correlation between orbital geochemistry results and backscatter; (3) echoes from a buried substrate (i.e., an interface between "soil" and rock at some depth) do not play a major role in the observed radar variation across the maria, and any such horizon must be a very poor backscatterer. These results indicate that the radar data may be sensitive to components in the soil (perhaps free iron in agglutinates) not well represented by the spectral ratio techniques, or that the radar echoes are a better TiO_2 mapping tool where the titanium content is below ~5%.

Radar returns at long wavelengths from the lunar regolith are affected by the surface and buried rock populations, the microwave loss tangent of the soil, and the presence of layering or substrates at depth [2, 3]. In order to analyze the nature of regolith scattering, we first "calibrated" the 70-cm polarized data to the full-disk measurements described by Hagfors [4]. The depolarized echoes were then shifted to produce the 3 dB difference in backscattered power at the limb observed in earlier studies. These data can be compared directly to backscatter coefficients measured by the NASA/JPL AIRSAR P-band radar system.

We selected thirty mare study sites which characterized the dynamic range across the nearside while avoiding the ejecta blankets of large fresh craters. The distribution of depolarized mare echoes is shown in Fig. 1, with the AIRSAR echoes for five Hawaiian lava flows presented for comparison. The mare areas typically fall below the lunar mean backscatter level, though there are several which are noteably brighter than this reference. These echoes fall between the two smooth pahoehoe flows of our Hawaii dataset, showing that the Moon is a relatively strong scatterer in comparison to very smooth rocky areas such as the Venus "dark" plains. The total dynamic range of the mare coefficients, representing the effects of radar loss tangent, rock population, and the nature and depth of any substrate, is about 8 dB.

Previous studies showed that variations in echo strength for the Mare Imbrium area were correlated with estimates of TiO_2 abundance obtained using the "Charette relationship" [5, 6, 7]. We plotted our 30 mare sites against the TiO_2 values produced by Johnson et al. [8], and found a poor overall correlation. While the TiO_2 content appears to define an upper limit for the radar echoes, there is wide scatter among the data. Similar results were found when the radar data were compared to Ti and Fe orbital geochemistry maps [9], but the low spatial resolution of these measurements makes quantitive analysis difficult. The lack of correlation between TiO_2 maps and radar results may be attributed to several possibilities: (1) the radar echoes are controlled by differences in rock population, (2) the echoes are changing due to variations in the depth and roughness of a substrate layer, (3) the loss tangent is affected by components which are not represented by the spectral ratio method, or (4) the calibration of the ratio method is not reliable below about the 5% abundance level.

The first two possibilities can be addressed by modeling of the radar echoes from different regolith structures. If a substrate exists, the degree of attenuation due to two-way passage of the energy through the soil can be calculated:

$$P(h) = P_o \exp \left[- \frac{8 \pi h}{\lambda \cos \phi} \sqrt{\frac{\varepsilon'}{2} \left[\sqrt{1 + \tan \delta^2} - 1\right]} \right]$$

where ϕ is the incidence angle in the soil, h is the depth of the layer, λ is the wavelength in vacuum, and ε' and $\tan \delta$ are the real dielectric constant and loss tangent of the soil. Using this equation and a reasonable range of loss tangents (0.002 to 0.02) derived from lab studies [10], we find that a substrate at >5 m depth would exhibit a dynamic range with $\tan \delta$ larger than that observed across the nearside maria. This result suggests that a sharply defined substrate does not exist, and that the transition from a rocky soil to coherent rock layers occurs gradually with depth such that we see no strong scattering horizon. The second possibility, that changes in rock population could dominate the radar signal, seems unreasonable in that the boundaries between radar-defined terrain units and those found in multi-spectral images are typically well correlated, and there should be no major mechanical (i.e, resistance to impact fragmentation) differences between mare lava flows of various compositions.

The last two possibilities seem most plausible. Free iron grains in agglutinates may play some role in changing the loss tangent of the lunar soil, so the radar may be measuring the bulk Fe content and maturity of the upper few meters of the regolith. Another scenario is that the radar echoes are a relatively direct indicator of the loss tangent, in which case the maps represent the total oxide content of the soil, perhaps to a better degree than the spectral ratio technique at low abundances (5% or less). Continued modeling of these data will seek to refine the results and to identify target areas for future 70-cm observations.

References: [1] Thompson, T.W., Earth, Moon and Planets, 37, 59-70, 1987; [2] Thompson, T.W. et al., Radio Science, 5, 253-262, 1970; [3] Hagfors, T., Radio Science, 2, 445-465, 1967; [4] Hagfors, T., Radio Science, 5, 189-227, 1968; [5] Schaber, G.G. et al., The Moon, 13, 395-423, 1975; [6] Charette, M.P. et al., JGR, 79, 1605-1613, 1974; [7] Pieters, C.M., Proc. LPSC 9, 2825-2849, 1978; [8] Johnson, J.R. et al., JGR 96, 18861-18882, 1991; [9] Davis, P., JGR, 85, 3209-3224, 1980; [10] Carrier, W.D. et al., in Lunar Sourcebook, 475-594, Cambridge Press, 1991.

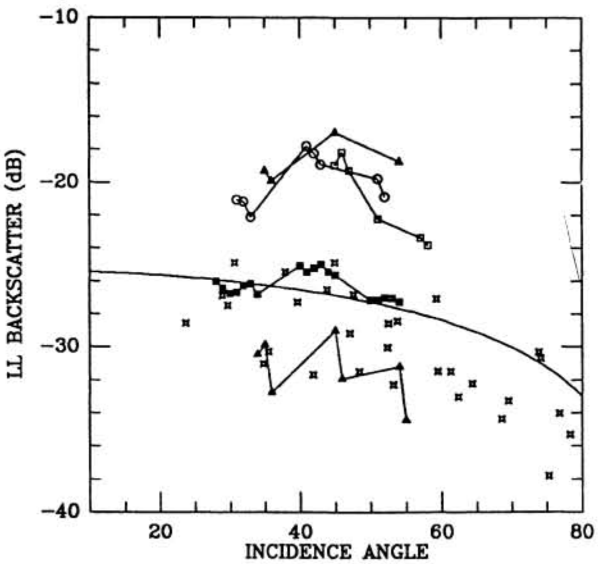

Fig 1. 70-cm depolarized echo strength versus incidence angle for mare sites (stars). Solid line shows lunar mean. Scattering behavior of five basalt flows shown for reference.

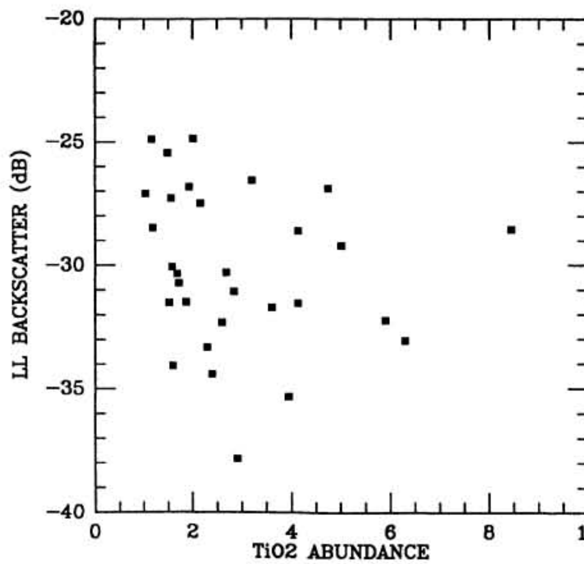

Fig. 2. 70-cm depolarized echo strength vs. TiO_2 abundance from [8].