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Surface Roughness and Rock Population of the Lunar Regolith: Results from 70-cm Arecibo Radar Observations

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Abstract

The Earth-based 70-cm Arecibo radar data of the lunar nearside are used to study the surface roughness and abundance and size of the buried rocks at 7 Lunar Orbiter sites and Apollo 12 landing sites. Using these results in combination with global geochemical maps, and known correlations between composition, density, and dielectric properties, these results will be extended to invert for a regolith thickness map over lunar nearside hemisphere.

1. Introduction

The physical characteristics of the lunar regolith not only provide important information concerning significant questions in lunar geology, but it is also critical for quantifying potential resources for future lunar exploration. For example, properties of buried rocks (size and population) are closely related to impact process and the evolution of the regolith, and surface roughness provides important information on engineering constrains for human outposts and rover trafficability. The regolith has been studied extensively using remote observations in the visible, infrared, and thermal infrared regimes. However, all these remote sensing techniques can only provide information for the uppermost surface layer of the regolith. Radar wave can penetrate several meters below the lunar surface and hence provide a complementary view about the regolith. In this study, Earth-based 70-cm Arecibo radar data and a quantitative radar scattering model are used to study the size, shape and population of the buried rocks in the regolith and the lunar surface roughness.

2. Model Description

We have developed a quantitative model for radar scattering from the lunar regolith layer based on vector radiative transfer (VRT) theory, which can take into account the transmission, attenuation, and scattering of radar waves from the lunar surface, and also the scattering from buried rocks and their interaction with the surfaces [1]. Multiple scattering between buried rocks is not taken into account. This model shows good comparisons with previous Earth-based radar observations of the lunar nearside and numerical simulations of Maxwell's equations. From this model, radar echo strengths can be predicted as a function of incidence angle, large-scale surface slope, regolith thickness, dielectric constant of the regolith, surface and subsurface roughness, and size, shape and population of buried rocks.

Several of the parameters in our model of the regolith layer can be estimated using other data sets. Dielectric permittivity of the regolith can be estimated using the measured relationship between the dielectric permittivity and bulk density and $FeO+TiO_2$ content, which can be obtained by γ-ray, X-ray and optical spectroscopy. Large-scale surface slope can be estimated using high-resolution topography, such as laser altimetry data. Regolith thickness at certain sites can be estimated using impact crater morphology and its size-frequency distribution, as well as direct seismic determinations at the Apollo landing sites. Among the remaining parameters, the main uncertainties are the size, shape, and population of the buried rocks, and the surface roughness.

The root mean square (rms) difference between the observed radar echo strengths σ^o and theoretical value σ from the VRT model is

$$\Delta\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[\sigma^{i}\left(\delta, l; a, c, f_s\right) - \sigma^{oi}\right]^2} \quad (1)$$

where δ and l are the rms height and correlation length of the surface that define the surface roughness, and a, c and f_s are the semi-minor, semi-major axes and fractional volume of the buried rocks. The radar echo strengths can be for the same sense, opposite sense, or the ratio of the two (the circular polarization ratio). As the rms difference between radar echo strengths reaches a minimum value, size, shape and population of the buried rocks, and lunar surface roughness can be estimated.

3. Results and Analysis

The Earth-based Arecibo radar images of the lunar nearside at 70 cm wavelength (frequency 430 MHz) are used in this study [2]. The data are obtained by transmitting a left circularly polarized radar signal and receiving in both the opposite and same sense polarizations (termed as "OC" and "SC") via a synthetic aperture radar patch–focusing reduction technique, with a spatial resolution of 320×450 m. The radiometric calibration uncertainty is 3 dB.

Using impact crater morphology and crater size-frequency distribution, *Oberbeck and Quaide* [3] estimated the regolith thickness at 12 regions using Lunar Orbiter imagery. By comparing with the Earth-based Arecibo data, 7 Lunar Orbiter sites, and the Apollo 12 landing site (the regolith thickness is available from passive seismic experiment [4]), are selected in this study. Table I lists the detail information of the 8 studying areas, including the site, position, regolith thickness (d), opposite-sense radar echo strengths (σ_{OC}) and radar incidence angle θ.

Table I Parameters of the studying areas

Site	Position	d (m)	σ_{OC} (dB)	θ (°)
I-P9.2b	3.5°S, 44.3°W	8-9	-22.6	43.3
II-P13	1.9°N, 41.2°W	5-5.5	-24.1	50.0
III-P8	0.9°S, 19.9°W	4.6	-15.6	27.5
III-P9c	3.2°S, 23.7°W	4.6	-13.8	22.8
III-P11	3.4°S, 36.8°W	3.3	-20.8	35.9
III-P12	2.8°S, 44.0°W	3.3	-22.3	43.0
V-38	32.7°N, 22.0°W	7.5	-25.6	46.0
A12	3.2°S, 23.4°W	3.7	-16.8	30.6

As an example, Figure 1 shows the opposite sense radar image of the Surveyor 1 landing site. Two studying areas in this region are Lunar Orbiter I-P9.2b and III-P12 site. The bright dots in Figure 1 are mostly caused by multiple scattering of the rocks at the crater rims, which is not considered in our model. Circular polarization ratio (CPR), which has a high value at crater rims [5], is used to exclude these bright points. An empirical threshold of CPR 0.2-0.3, which depends on radar incidence angle, is chosen.

Our preliminary result shows that, at these 8 studying area, the rms slope of lunar surface is about 4.8° at the scale of 70 cm wavelength, while the population of buried rocks is about 0.5 per m^3 with a radius around 6 cm. Detail inversion results and their comparison with rock properties at the Surveyor landing sites will be presented at the conference.

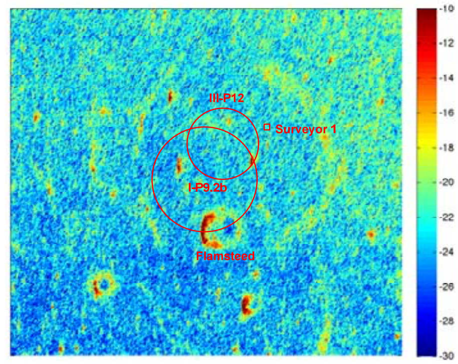

Figure 1. Opposite-sense radar image (dB) of the Surveyor 1 landing sites, Lunar Oribiter I-P9.2b and III-P12 site are two areas in this study.

4. Conclusions

Using the Earth-based 70-cm Arecibo radar data of the Moon and a quantitative radar scattering model, surface roughness and properties of buried rocks at 7 Lunar Orbiter sites and the Apollo 12 landing site are estimated. Preliminary result shows the rms slope of the lunar surface is 4.8°, and the population of buried rock in the regolith is about 0.5 per m^3 with a size around 6 cm. These estimated parameters will be extended globally to invert for the lunar regolith thickness using the Earth-based 70-cm radar data and Mini-SAR data from Chandrayaan-1 and LRO.

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