A PRELIMINARY INVERSION OF LUNAR REGOLITH THICKNESS USING EARTH-BASED 70-CM ARECIBO RADAR OBSERVATIONS. Wenzhe Fa and Mark A. Wieczorek, Institut de Physique du Globle de Paris - Sorbonne Paris Cité, 4 Avenue de Neptune, Saint-Maur des Fossés, 94100, France (wzfa@ipgp.fr).

Introduction. Previous investigations have shown that almost the entire lunar surface consists of a fine-grained regolith layer that completely covers the underlying bedrock. The lunar regolith is a byproduct of the continuous impact of large and small meteoroids with the lunar surface, and its thickness has been estimated to be about 4-5 m for the maria and 10-15 m for the older highlands [1]. Knowledge of the structure, composition and distribution of lunar regolith provides important information about both lunar geology and potential resources for future lunar exploration.

The regolith thickness has been estimated previously for a few localized regions using direct measurements made during the Apollo missions (such as seismic and multifrequency electromagnetic probing experiments) [2, 3]. Regolith thickness over larger regions (as well as its statistical distribution) has been estimated as well using impact crater morphology and crater size-frequency distributions [4]. More recently, remote sensing techniques, such as Earth-based radar [5], Chang-E microwave radiometry [6], and Kaguya lunar radar sounding [7], have been used to invert for regolith thickness over larger regions. However, uncertainties in the calibration of these remote-sensing data sets and the use of a simplified regolith model that did not consider buried rocks have limited the utility of these techniques [5-7].

In this study, a rigorous radar scattering model based on vector radiative transfer theory and Earth-based 70-cm radar data are used to invert for regolith thickness over the entire lunar nearside hemisphere.

Regolith thickness inversion approach. Newly acquired well-calibrated Earth-based Arecibo radar data [8] are used for our regolith thickness inversions. The radar frequency is 430 MHz (corresponding to a 70 cm wavelength), the spatial resolution is about 400 m, and the calibration uncertainty is ±3 dB. The nominal penetration depth of the radar wave in the lunar regolith is from 1 to 30 m, depending on regolith composition.

We have developed a quantitative model for radar scattering from the lunar regolith layer based on vector radiative transfer theory that takes into account the transmission, attenuation and scattering of radar waves from the lunar surface, and the scattering from buried rocks [9]. Multiple scattering between buried rocks is not taken into account. This model shows a good comparison with Earth-based radar observations of the lunar nearside and numerical simulations of Maxwell's equations, especially for the opposite sense radar echo strength. From this model, radar echo strengths can be predicted as a function of incidence angle, large-scale surface slope, regolith thickness, dielectric permittivity of the regolith, surface and subsurface roughness, and size, shape and abundance of buried rocks.

If the dielectric constant of the regolith (ε), lunar surface roughness (rms slope s), and rock abundance (n_0, rock number per m^3) and size (radius r) are known from other data sets, the regolith thickness (d) can be estimated by minimizing the difference between the observed and modeled radar back scattering coefficients. In this study, the opposite sense radar echo strengths are used for regolith thickness inversions since they are less sensitive to multiple scattering that is difficult to model [9].

Model input parameters. Three parameters are found to be critically important in our radar scattering model: lunar regolith dielectric permittivity, surface roughness, and subsurface rock size and abundance.

We have first reanalyzed the measured dielectric properties of the Apollo regolith samples [1]. Our reanalysis shows that, when normalized to a specific density (assuming the regolith is a mixture of mineral grains and vacuum), the relative dielectric permittivity of the regolith is constant and that the loss tangent depends only on the abundance of TiO_2 (i.e., abundance of ilmentite). The bulk density of the lunar regolith over the lunar surface is first estimated using a relation between the regolith density and its composition [10, 11] and the complex dielectric permittivity is then estimated using a mixing relation with an assumed 50% porosity. Results show that the real part of the dielectric constant varies from 2.4-3.2, and the loss tangent varies from 0.004-0.012.

To constrain the lunar surface roughness and size and abundance of buried rocks, 9 regions (3 Apollo landing sites, 2 Surveyor landing sites, and 4 other regions) are selected as calibration sites, where the regolith thickness and composition are known [1, 4]. Model simulations show that different combinations of lunar surface roughness, rock size and abundance can produce similar radar echoes that match equally well the Arecibo radar observations at these sites. From the viewpoint of radar scattering, scattering from the lunar surface and buried rocks cannot be perfectly distinguished, and there is a tradeoff between rock size and abundance. We find that for a given backscattering coefficient, there is a nonunique relationship between n_0r^6 and rms slope s that fits the data equally well. This relation gives an upper bound on the permissible surface roughness, showing that the lunar surface in general has rms slopes less than 10° at radar wavelength scale. If the lunar surface roughness could be estimated from high-resolution topography data [12], then the product $n_0 r^6$ could be uniquely estimated.

Preliminary results and discussion. The constrained relations of permissible values $n_0 r^6$ and lunar surface roughness at the calibration sites are used as guidelines for the selection of globally representative parameters in our regolith thickness inversions. Using a lunar surface roughness of 3°, a rock radius of 3 cm and a rock abundance of 40 m^{-3}, Figure 1 shows the inverted regolith thickness for a region close to Surveyor 1 landing site (region 9.2b in [4]). The average regolith thickness at this site was estimated to be 8-9 m from the study of impact crater morphology and crater size-frequency distributions [4]. Figure 2 shows the cumulative distribution of regolith thickness at this site from crater morphology [4] and radar based inversions [5]. The black line is our inversion result, whereas the red line is from Shkuratov and Bondarenko [5]. It can be seen that our results match better those of Oberbeck and Quaide [4]. The model of Shkuratov and Bondarenko [5] used the same sense radar echo strength (in contrast to the opposite sense data in this study), and did not model the effects of buried rocks.

Taking a typical value of the rms surface slope of 3° for maria and 5° for highlands, a rock radius of 3 cm and a rock abundance of 30 m^{-3}, the regolith thickness over Mare Crisium, Oceanus Precellarum and two highland areas were inverted. Our inversion results show that the regolith thickness for Mare Crisium varies from 2 to 10 m (Figure 3), whereas that of Oceanus Precellarum is in general less than 5 m. The regolith thickness of the highlands region varies from several meters to more than 15 m.

We are currently applying this approach in combination with surface roughness obtained from the LRO laser altimeter data [12] to obtain improved regolith thickness over the lunar nearside hemisphere.

References. [1] Heiken G., et al. (1991), New York: Cambridge Univ. Press. [2] Nakamura Y., et al. (1975), *Moon*, 13, 3-15. [3] Strangway D., et al. (1975), Moscow: Nauka, 712-728. [4] Oberbeck V. and W. Quaide (1967), *JGR*, 72, 4697-4704. [5] Shkuratov Y. and N. Bondarenko (2001), *Icarus*, 149, 329-339. [6] Fa W. and Y.-Q. Jin (2010), *Icarus*, 207, 605-615. [7] Kobayashi T., et al. (2010), *IEEE Geosci. Remote Sen. Lett.*, 7(3), 435-439. [8] Campbell B., et al. (2007), *IEEE Trans. Geosci. Remote Sen.*, 45, 4032-4042. [9] Fa W., et al. (2011), *JGR*, 116, 2010JE003649. [10] Huang Q. and M. Wieczorek, EPSC 2010, Abstract #578. [11] Prettyman T. H., et al. (2006), *JGR*, 111, 2005JE002656. [12] Rosenburg M. A., et al. (2011), *JGR*, 116, 2010JE003716.

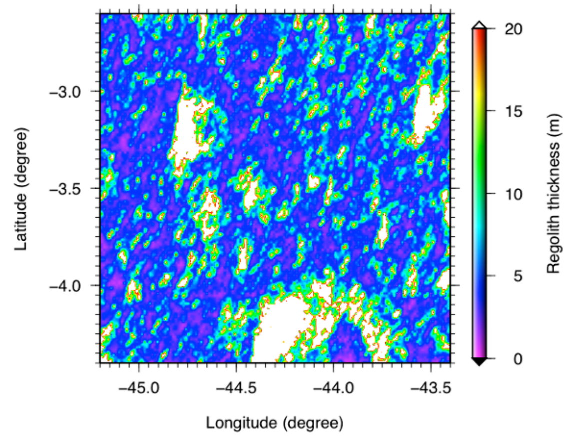

Figure 1. Inverted regolith thickness for a region close to the Surveyor 1 landing site (site 9.2b in [4]). The average regolith thickness at this site was estimated to be 8-9 from crater morphology study [4].

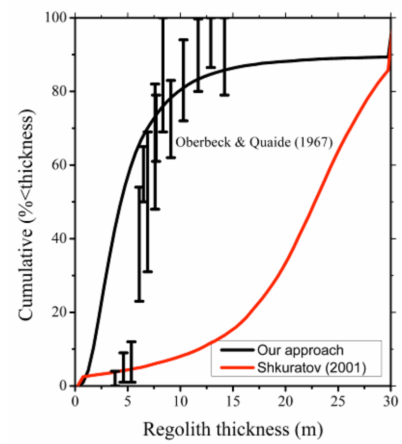

Figure 2. Cumulative distribution of regolith thickness for the region in Figure 1. The black line represents the results from this study, the red line is from Shkuratov and Bondarenko [5], and the data with associated error bars are from the crater morphological investigations of Oberbeck and Quaide [4].

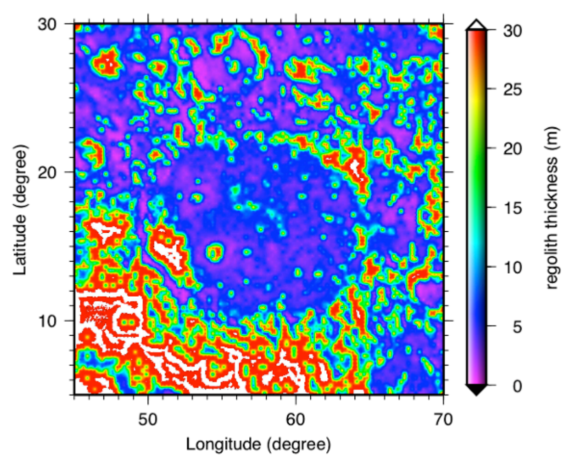

Figure 3. Inverted regolith thickness in the region of Mare Crisium.