A Preliminary Inversion of Lunar Regolith Thickness Using Earth-based 70-cm Arecibo Radar Observations

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1. INTRODUCTION

Lunar Regolith

Previous investigations have shown that almost the entire lunar surface consists of a fine-grained regolith layer that completely covers the underlying bedrock. The thickness of the regolith is an indication of the age of the lunar surface, and it is important for landing site selection for future missions, such as for heat flow experiments. The regolith also contains valuable resources and volatiles, and future human activates will use regolith for building materials and shielding. Knowledge of the lunar regolith thickness is important for both science and engineering reason.

Previous Approaches

1. Direct in situ measurement during Apollo missions, such as seismic and multifrequency electromagnetic probing experiments [1, 2].
2. Study of impact crater morphology and crater size-frequency distributions [3].
3. Remote sensing techniques, such as Earth-based radar [4], Chang-E microwave radiometer [5], and Kaguya lunar radar sounder [6].

Purpose of This Study

Obtain a regolith thickness map for the lunar nearside hemisphere using a rigorous radar scattering model and the newly acquired Earth-based 70-cm Arecibo radar data.

2. RADAR SCATTERING MODEL AND DATA

Radar Scattering Model

Vector radiative transfer is used to calculate the radar echo from the lunar surface. The radar echo contains scattering from the rough surface and subsurface, volume scattering from buried rocks, and interactions between surface, subsurface and buried rocks.

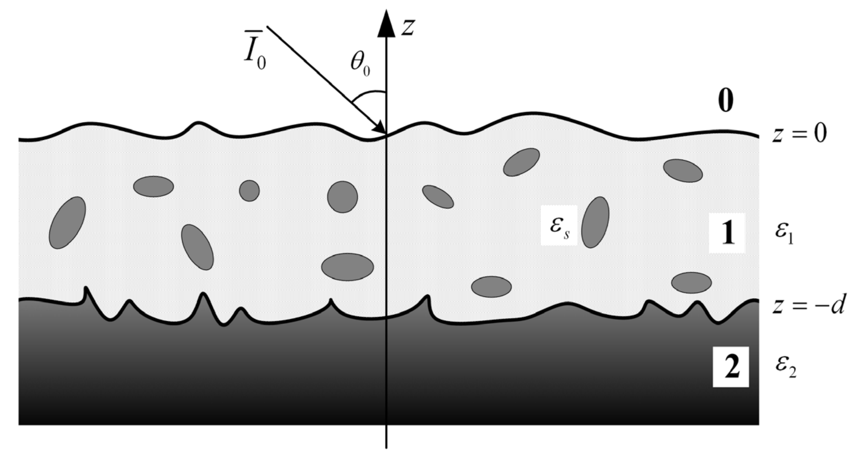


Figure 1. Schematic diagram of radar scattering model [7].

Earth-based 70-cm Arecibo Radar Data

The radar data have a nominal penetration depth of 1-30 m depending on the composition of the regolith, a spatial resolution of 400 m, and a calibration uncertainty of 3 dB.

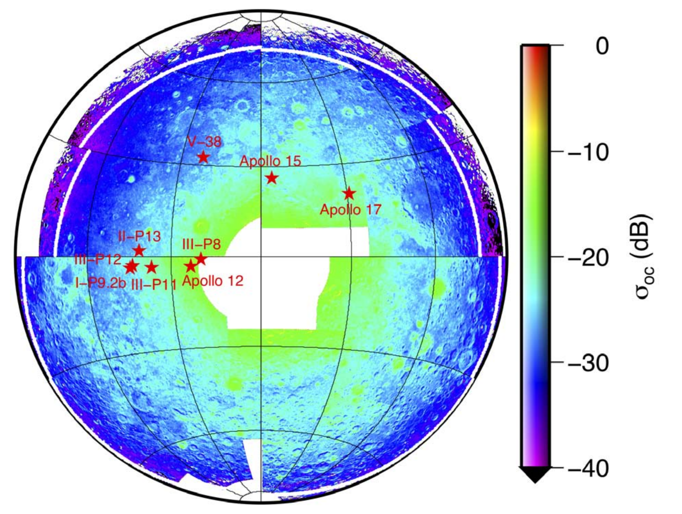


Figure 2. Opposite sense radar image [8]. The red stars mark the locations where the regolith thickness has been estimated by either direct methods or by using the size-frequency distribution of small impact craters. The white line shows where the radar incidence angle is 80 degree, which is the maximum that can be utilized in our radar scatting model.

3. DIELECTRIC CONSTANT OF THE REGOLITH

Our reanalysis of the Apollo regolith dielectric measurements shows that when normalized to a constant bulk density (or porosity), the real part of the complex dielectric constant is constant, and the loss tangent is only correlated with TiO_2 content. This is in contrast to the analysis by Carrier et al. [9] who suggested that the loss tangent depended upon the total $FeO+TiO_2$ content. The dependence of the dielectric constant on bulk density can then be calculated using the Maxwell-Garnett mixing rule.

$$\varepsilon' = 2.75, \quad \log_{10}(\tan\delta) = -2.395 + 0.064\,TiO_2 \quad (\rho = 1.7\,g/cm^3)$$

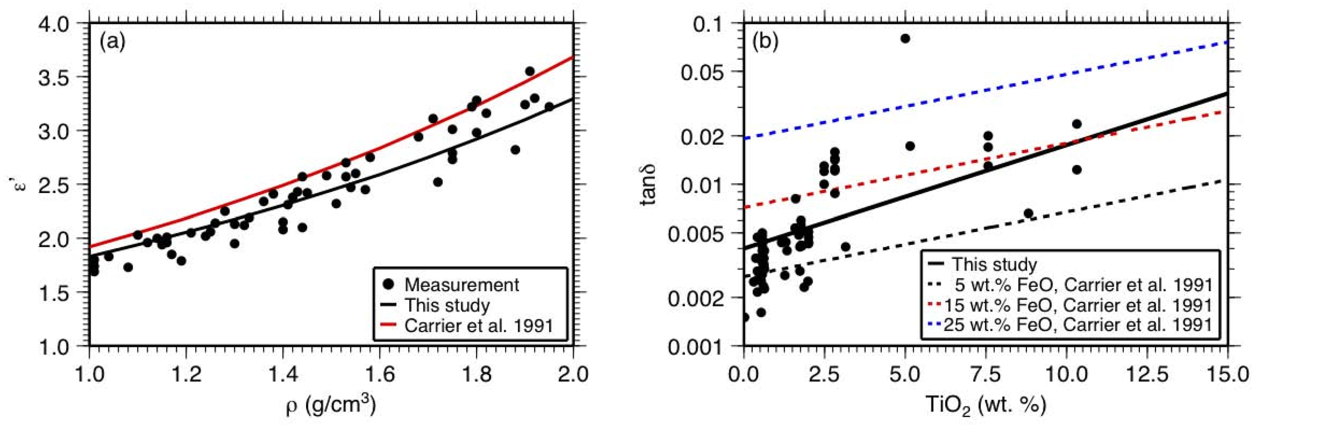


Figure 3. (a) Real part of the complex dielectric constant as a function of bulk density. (b) Loss tangent as a funtion of the TiO_2 abundance (wt. %).

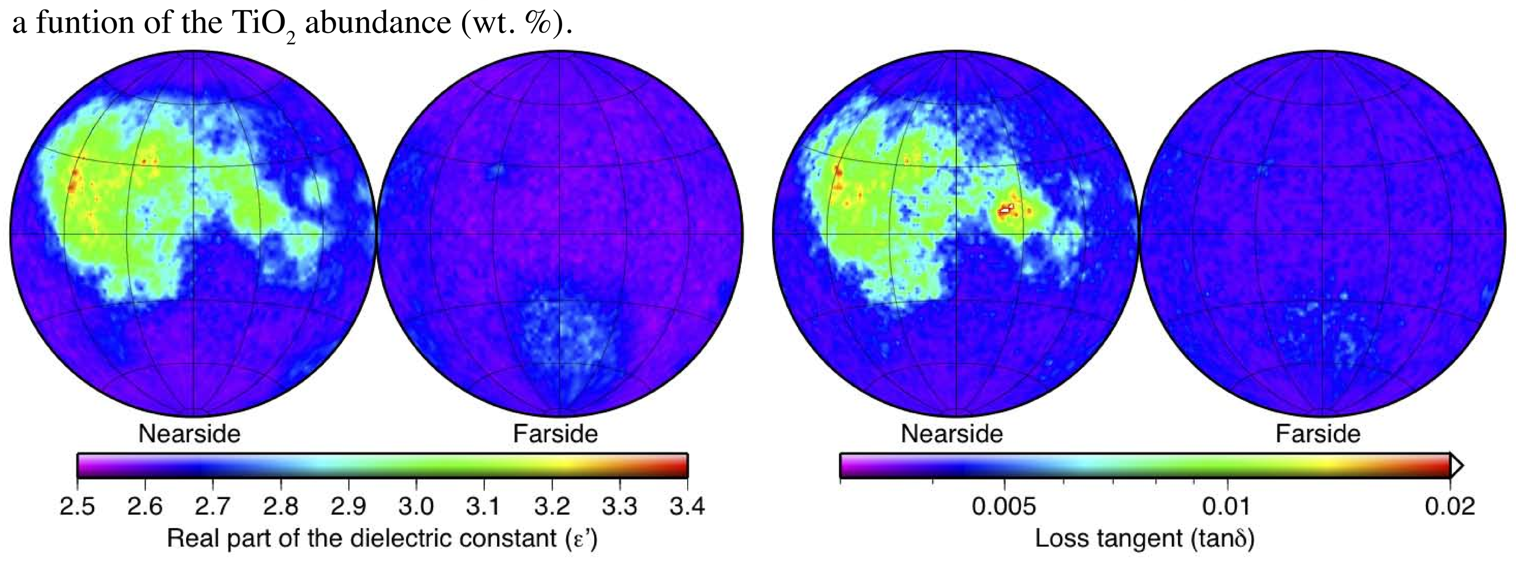


Figure 4. Dielectric constant of the regolith over the lunar surface: (left) real part and (right) loss tangent.

4. CONSTRAINTS ON LUNAR SURFACE ROUGHNESS AND SIZE AND ABUNDANCE OF BURIED ROCKS

Model simulations show that various combinations of lunar surface roughness, rock size and abundance can produce radar echoes that match equally well the Arecibo radar data at each calibration sites (stars in Figure 2). By using the known regolith thickness from previous studies [1,2], we found that the appropriate tradeoff involves the parameter $n_0 r^6$, as predicted by Rayleigh scattering of spheres, where n_0 is the number of rocks per m^3 and r is the rock radius.

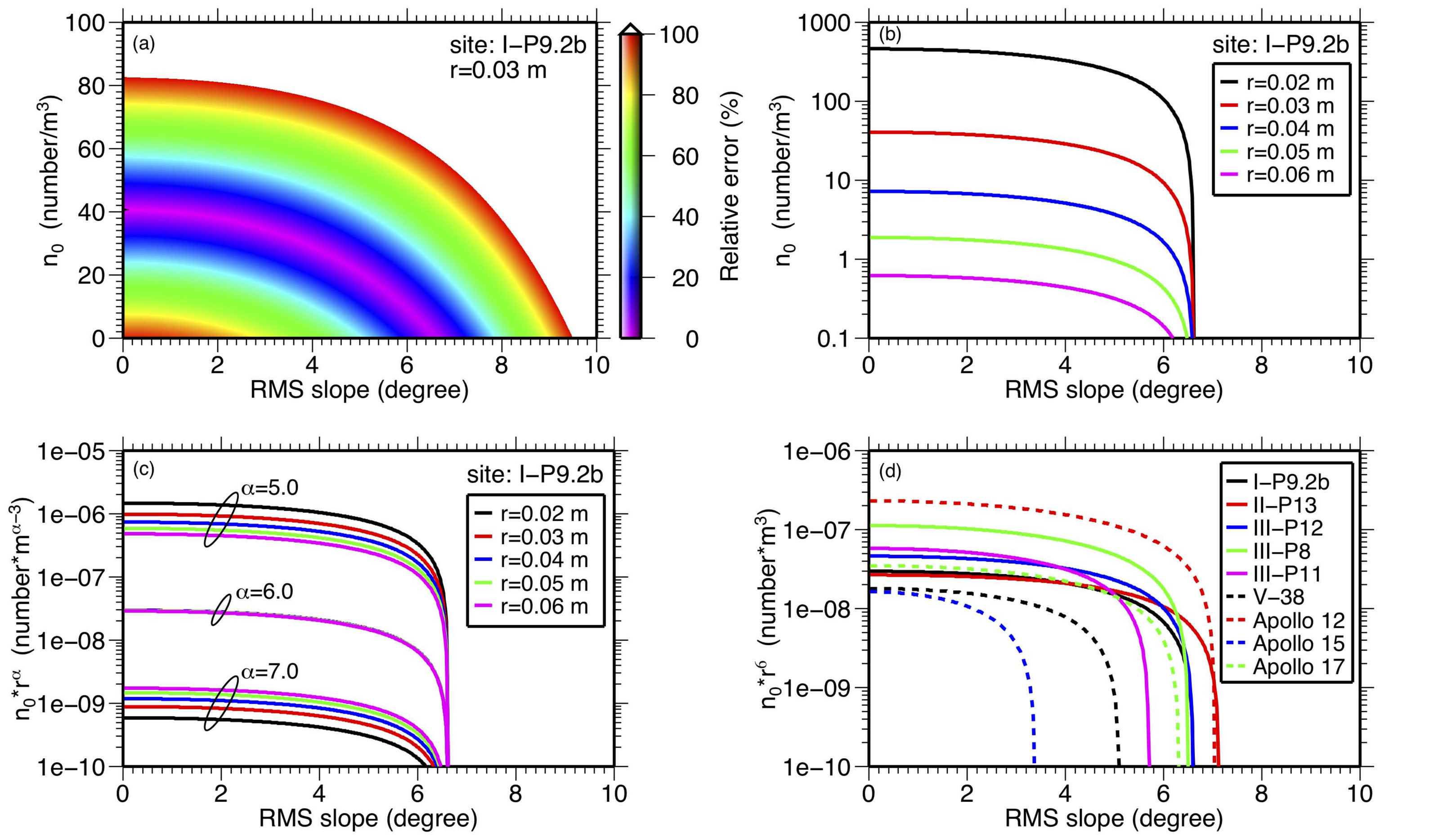


Figure 5. (a) Relatvie error of the radar echo strength as a function of rock abundance and RMS slope for site I-P9.2b for a given rock size. (b) Best fit model as a function of rock abundance and RMS slope for several different rock sizes. (c) Best fit model as function of $n_0 r$ and RMS slope, and for = 5, 6, 7. (d) Best fit model as a function of $n_0 r^6$ vs. RMS slope for 9 sites over the lunar nearside.

5. UPPER LIMIT OF THE LUNAR SURFACE ROUGHNESS

The trade off relation at the calibration site gives an upper bound on the lunar surface roughness, which varies with the radar incidence angle.

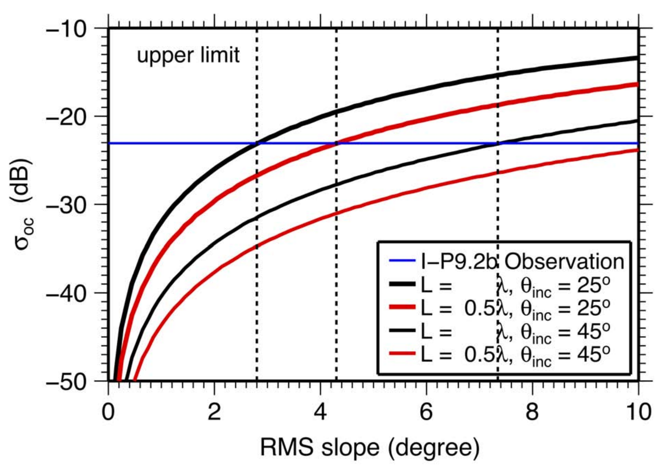


Figure 6. Principle for determining the upper limit of lunar surface roughness, where L is the correlation length of the lunar surface, is the wavelength.

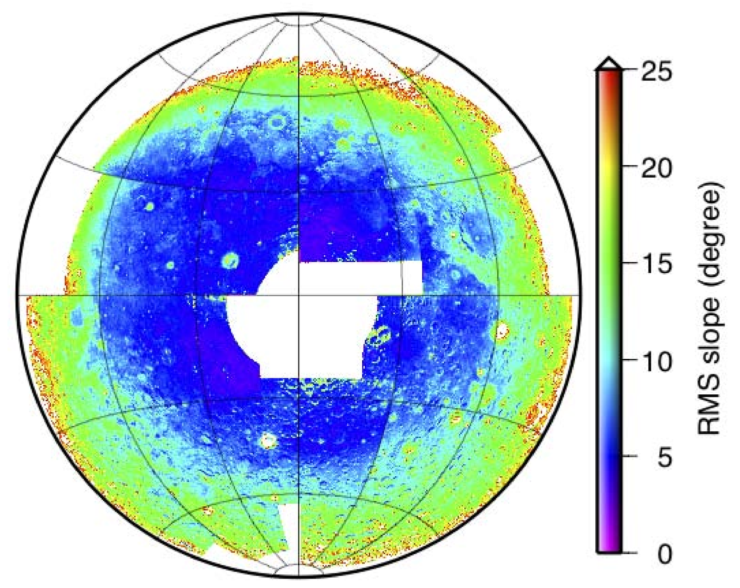
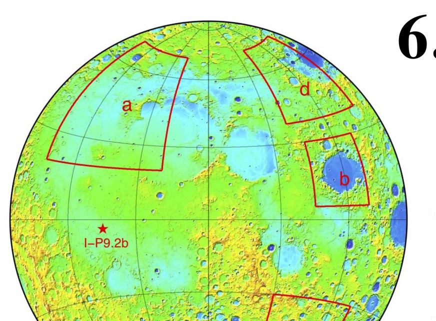


Figure 7. Upper limit of lunar surface roughness (RMS slope) with L equal to .

6. PRELIMAINARY RESULTS AND CONCLUSIONS

6.1. Validation of Inverted Regolith Thickness



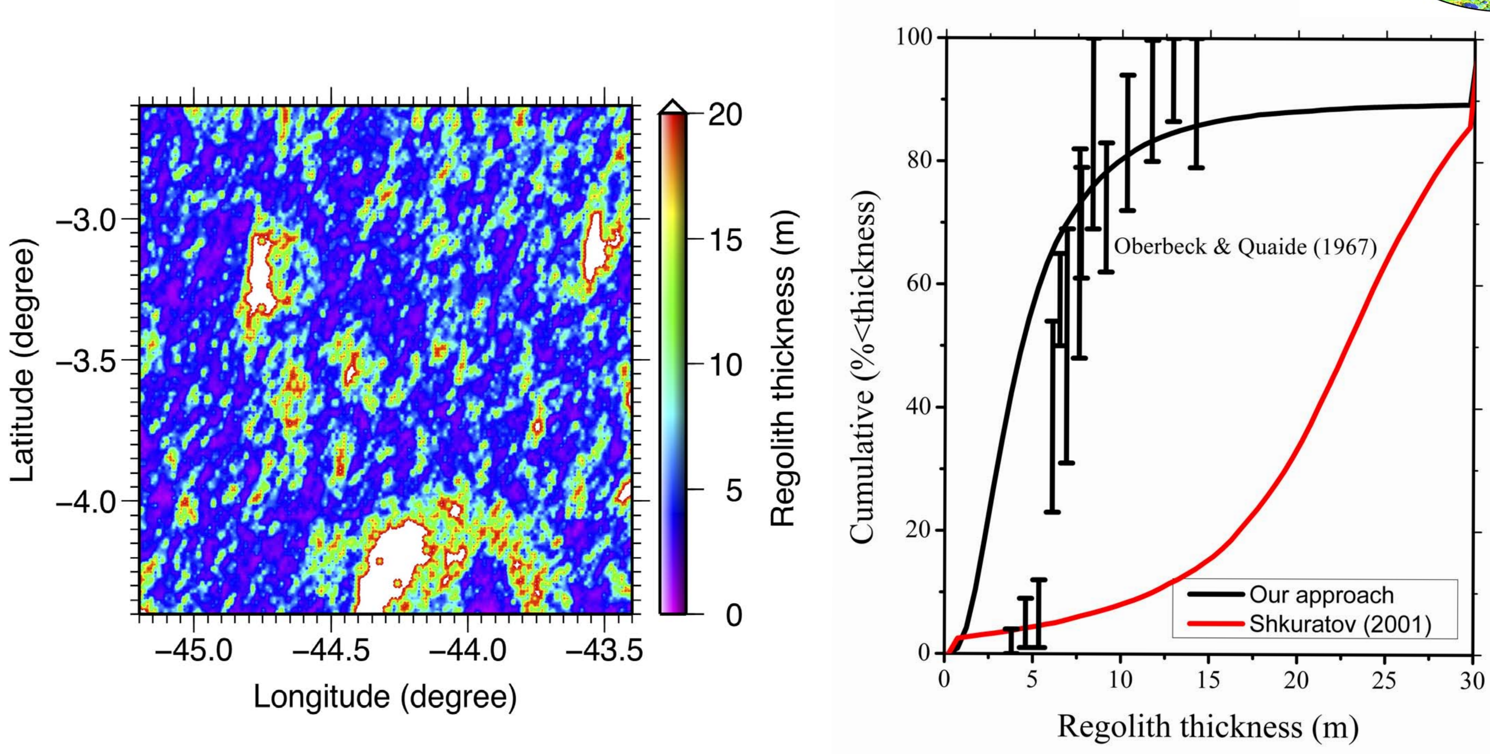


Figure 8. (Left) Inverted regolith thickness at site I-P9.2b (close to Surveyor 1 landing site), where the RMS slope is assumed to be 3°, the rock number is taken to be 40/m³ and the rock radius is set to 3 cm (values are from Figure 5). The average regolith thickness at this site is estimated to be 8-9 m by Oberbeck and Quaide [3]. (Right) Cumulative distribution of regolith thickness for the regions at site I-P9.2b showing our results (black line), Oberbeck and Quaide (data with error bars) [3] and Shkuratov and Bondarenko [4] who used a different radar scattering model and radar dataset.

6.2. Inversion Results of Regolith Thickness

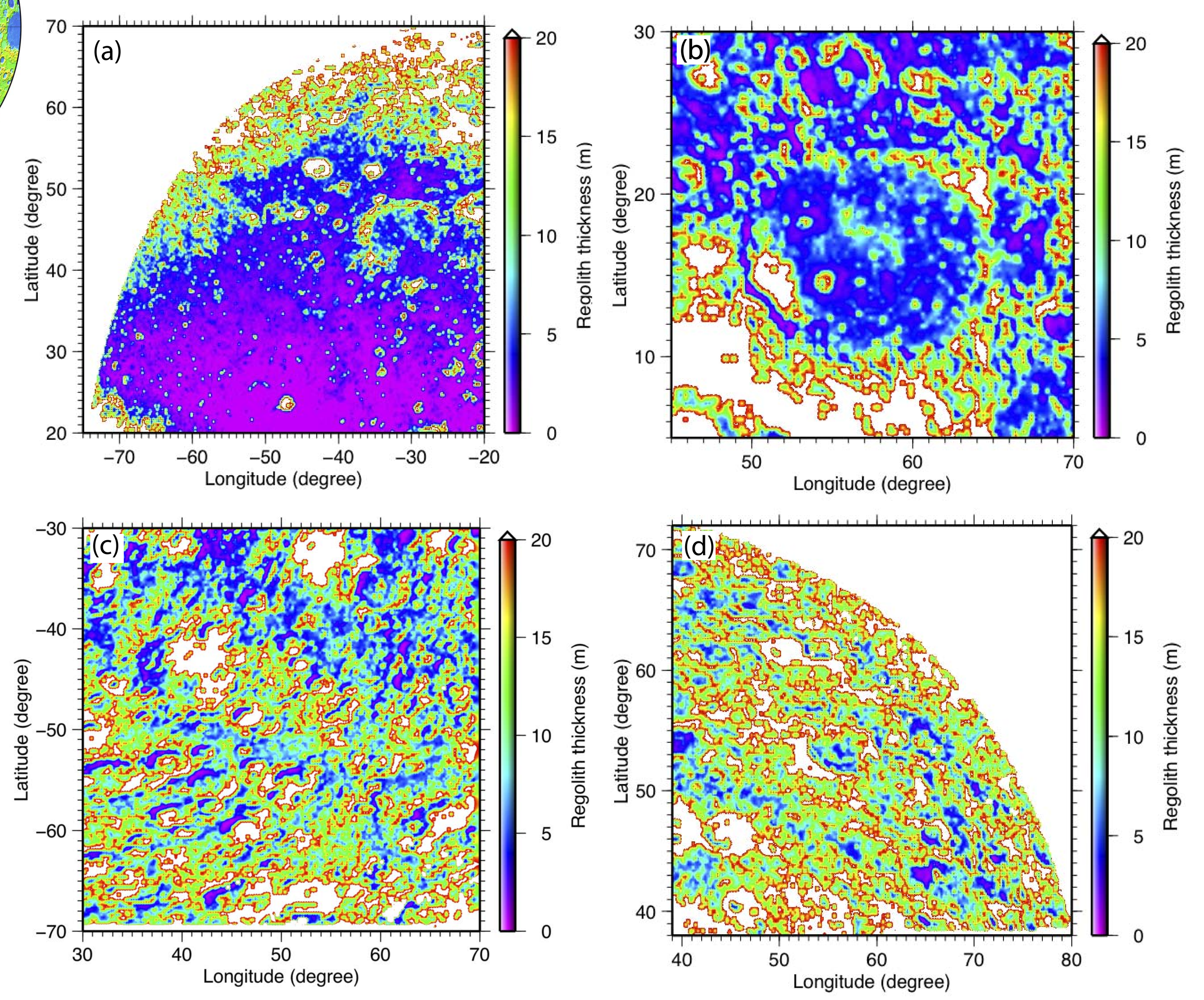


Figure 9. Inverted regolith thickness over (a) noth part of Oceanus Procellarum, (b) region of Mare Crisium, (c) highlands 1 and (d) highlands 2, where the RMS slope is assumed to be 3° for maria and 5° for highlands, the rock size is taken as 3 cm and the abundance of buried rock is set to be 30/m³.

6.3. Conclusions

1. The loss tangent of the lunar regolith depends only on TiO_2 content, and not $FeO+TiO_2$ content as previously assumed.
2. If we can estimate the lunar roughness from high resolution topography data, then rock abudance and size could be estimated from radar observations.
3. Preliminary inversion results show that the average regolith thickness over the maria is no more than 6 m, whereas that of the highlands could be more than 10 m.
4. To get accurate regolith thickness, well-calibrated radar data is necessary, and we need to know the size and abundance of buried rocks and lunar surface roughness.

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