

DETERMINATION OF THE PERMITTIVITY OF THE LUNAR SURFACE BASED ON THE RADAR ECHO INTENSITY OBSERVED BY THE KAGUYA. A. Kumamoto¹, T. Ono¹, T. Kobayashi², S. Oshigami³, and J. Haruyama⁴, ¹Graduate School of Science, Tohoku University (Aoba, Aramaki, Aoba, Sendai 980-8578, Japan. E-mail: kumamoto@stpp.gp.tohoku.ac.jp), ²Korea Institute of Geoscience and Mineral Resources, ³National Astronomical Observatory of Japan, ⁴Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency.

Introduction: The permittivity of the lunar surface is considered to depend on the compositions and porosity of the surface materials. Therefore the determination of the permittivity will enable us to discuss the geological conditions of the lunar surface. Because the reflectivity of the electromagnetic waves between two media depends on their permittivity, we might expect that we can use the radar echo intensity for determination of the permittivity. However, the situation is not so simple because the radar echo intensity depends not only on the permittivity but also on the roughness of the surface. Therefore, we have determined the permittivity of the lunar surface with considering the surface roughness. In the analysis, the permittivity is determined by using the radar echo intensity obtained by Kaguya Lunar Radar Sounder (LRS) [1, 2, 3, 4], and the surface roughness parameters derived from Digital Terrain Model (DTM) based on Kaguya Terrain Camera (TC) observation [5].

Analyses Method: The global distributions of the echo powers in a frequency range of 4-6 MHz were derived from the Kaguya/LRS dataset. The Kaguya spacecraft moved along the polar orbit with an altitude of about 100 km. In order to achieve enough range resolution, Kaguya/LRS transmitted chirp pulse with a bandwidth of 2MHz. The range resolution of LRS in vacuum is therefore 75m. The transmission power of Kaguya/LRS was 800 W [1, 2, 3, 4]. We have used the intensity of off-nadir echoes in an incident angle larger than 3 degree. The reason why nadir echoes are not used in the analysis is because the echo intensity changes drastically in small incident angle especially at the smooth surface. The echoes arrived after the arrival of the nadir surface echo were identified as off-nadir echoes in this study. We should note that the echoes arrived after the arrival of the nadir surface echo consists of various components such as off-nadir surface echoes, volume scatters from the materials below the surface, and echoes from the subsurface reflectors. In the present analysis, we assumed that most of them was off-nadir surface echoes. The off-nadir echo intensities were derived in 180 x 90 areas divided by 2 degree longitude x 2 degree latitude grid.

In addition, we have also derived the global distribution of the surface roughness parameters. The RMS

height v , or Allan deviation of the surface height, can be obtained by

$$\{v(\Delta x)\}^2 = \langle \{h(x + \Delta x) - h(x)\}^2 \rangle, \quad (1)$$

where $h(x)$ is height of the surface derived from the Kaguya TC/DTM, Δx is baseline length, and $\langle \rangle$ denotes the average. If we assume the self-affine surface model, the roughness parameters H and s can be obtained by the least square fitting of the RMS heights to

$$v(\Delta x) = s\Delta x^H. \quad (2)$$

The roughness parameters were derived in 180 x 90 areas divided by 2 degree longitude x 2 degree latitude grid. As for Hurst exponent H , the global distribution has been reported based on the Lunar Reconnaissance Orbiter (LRO) laser altimeter data [6]. The off-nadir surface echo power can be calculated based on the radar equation. Assuming Kirchhoff Approximation (KA), the backscattering coefficient in the radar equation can be obtained from the roughness parameters H and s , and permittivity [cf. 7, 8, 9].

Using the roughness parameters H and s obtained by Kaguya TC/DTM and changing the assumed permittivity, we can calculate the expected off-nadir surface echo powers and compare them with observed off-nadir surface echo power. Based on the comparison, we can determine most plausible permittivity.

Results: The global maps of roughness parameters, H and $\log_{10}(s)$, are shown in Figs. 1 and 2. The Hurst exponent H is less than 0.5 in the maria, and about 0.9 in the highlands. The parameter s is about 1 in the maria, and about 0.3 in the highlands. The global distribution of H is similar with that based on LRO [6]. By applying the analysis method mentioned above, we could obtain the observed and calculated surface echo powers in the regions where $0.25 < H < 0.35$, and $0.85 < H < 0.95$ as shown in Figs. 3 and 4. Based on them, we could estimate the average permittivity in the maria ($H \sim 0.3$) to be 4-5, and that in the highlands ($H \sim 0.9$) to be 2.

Discussion: It is inferred that the lunar basalt below the surface consists of grains and voids. The bulk permittivity of the lunar uppermost basalt layer depends on the permittivity of the grains and the ratio of the voids, or porosity. According to the previous studies based on the Apollo lunar samples [cf. 10], the grain permittivity can be estimated by

$$\varepsilon_{r,grain} = 0.74 \exp[0.85(0.0165S + 2.616)], \quad (3)$$

where $S = \text{FeO}$ [wt.%] + TiO_2 [wt.%] is abundance of the ilmenite in the lunar basalt. The abundance of the ilmenite can be derived also from the Clementine multiband image data [11]. So we can estimate the porosity n of the lunar basalt by

$$n = 1 - \frac{\ln(\varepsilon_{r,bulk}/0.74)}{\ln(\varepsilon_{r,grain}/0.74)}, \quad (4)$$

where $\varepsilon_{r,bulk}$ is the bulk permittivity measured with including voids in the lunar basalt [10, 12]. Based on the bulk permittivity determined in this study, we could estimate the porosity in the maria ($H \sim 0.3$) to be 30 % and that in the highland ($H \sim 0.9$) to be 60 %. It is considered that the surface of the highlands is older than that of the maria. Due to long-time exposure to the impacts of the meteolites, the porosity of the lunar basalt in the highlands can be larger than that in the maria. In future work, we will be able to discuss the local geological conditions by performing the determination of the permittivity and porosity of the lunar basalt in each region.

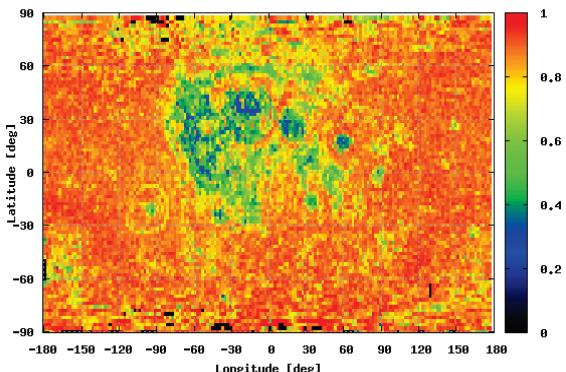


Figure 1: Global map of Hurst exponent H . H is less than 0.5 in the maria, and about 0.9 in the highlands.

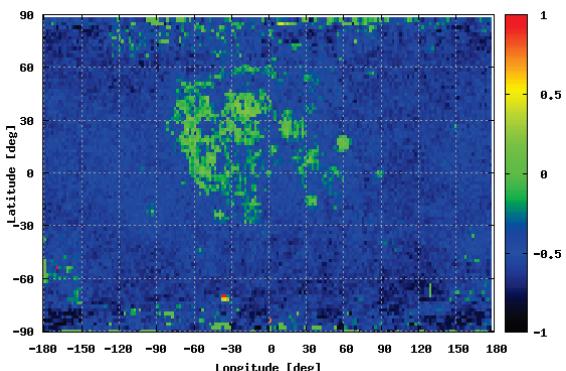


Figure 2: Global map of $\log_{10} s$. The parameter s is about 1 in the maria, and about 0.3 in the highlands.

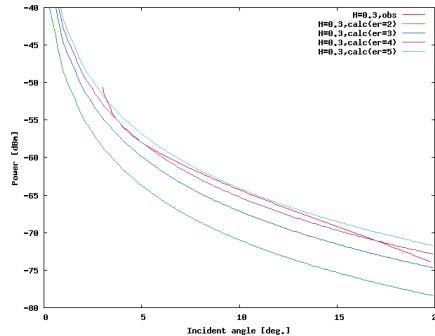


Figure 3: Observed and calculated surface echo power as a function of incident angle in the regions where $0.25 < H < 0.35$. Observed echo power (red curve) is almost equal to the echo powers calculated with assuming permittivities of 4 and 5 (magenta and light blue-curves, respectively).

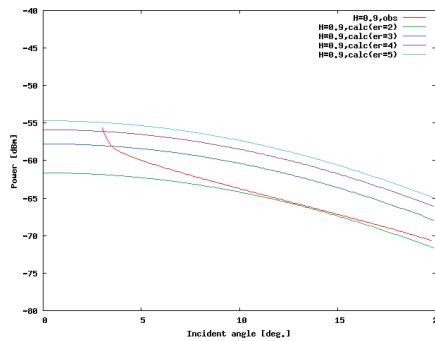


Figure 4: Observed and calculated surface echo power as a function of incident angle in the regions where $0.85 < H < 0.95$. Observed echo power (red curve) is almost equal to the echo power calculated with assuming permittivity of 2 (green curve).

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