Wideband Microwave Radiometry for Remote Sensing of Lunar Regolith and Bedrock

Mustafa Aksoy[1]

[1]University at Albany State University of New York

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Abstract

The lunar surface consists of a regolith layer, i.e., fragmental and unconsolidated rock material of highly varied character, which covers the underlying bedrock. Understanding the structure and composition of the lunar regolith and the underlying bedrock is very important to reveal geologic features of the Moon, explore natural resources humans can exploit, and obtain valuable information regarding the history of the solar system. Electromagnetic radiations from the surface of the Moon at microwave frequencies depends on the physical, chemical, and electrical properties of the regolith layer and the bedrock. Moreover, the electromagnetic penetration depth changes with frequency which allows wideband microwave radiometers operating below 50 GHz to conveniently profile these properties versus depth to characterize the lunar regolith and bedrock with wide spatial coverage. Combining current models of depth-dependent physical and chemical properties with simple electromagnetic forward radiation models, surface emissions over the Apollo sites were simulated and compared with Chinese Chang'E-1 and Chang'E-2 multi-frequency microwave radiometer measurements. Potential sources of the differences between the simulations and measurements have been identified as the temperature dependence of the electrical properties of the regolith, bedrock type, surface and bedrock roughness, as well as density fluctuations, scattering due to inhomogeneities, and coherent interference of electromagnetic fields within the regolith. However, many of these subjects have been studied thoroughly for the remote sensing of the cryosphere; thus leveraging this experience with the rapid developments in radiometer designs, wideband microwave radiometers promise valuable scientific returns in future lunar missions.

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Mustafa Aksoy
University at Albany, State University of New York

UNIVERSITY AT ALBANY
State University of New York

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1. MOTIVATION

The lunar surface consists of a regolith layer, i.e., fragmental and unconsolidated rock material of highly varied character, which covers the underlying bedrock. Understanding the structure, composition, and dynamics of the lunar regolith and the underlying bedrock is very important to reveal geologic features of the Moon, explore natural resources humans can exploit, and obtain valuable information regarding the history of the solar system.

Electromagnetic radiations from the surface of the Moon at microwave frequencies depend on the physical, chemical, and thermal properties of the regolith layer and the bedrock. Moreover, the electromagnetic penetration depth changes with frequency which may allow wideband microwave radiometers operating below 50 GHz to conveniently profile these properties versus depth to characterize the lunar regolith and bedrock with wide spatial coverage.

2. PHYSICAL AND ELECTRICAL PROPERTIES OF LUNAR REGOLITH

Regolith Density

$$\rho(z) = 1.92\frac{z-12.2}{z+18}$$

where ρ is the bulk density in g/cm^3 and z is the depth in cm [1].

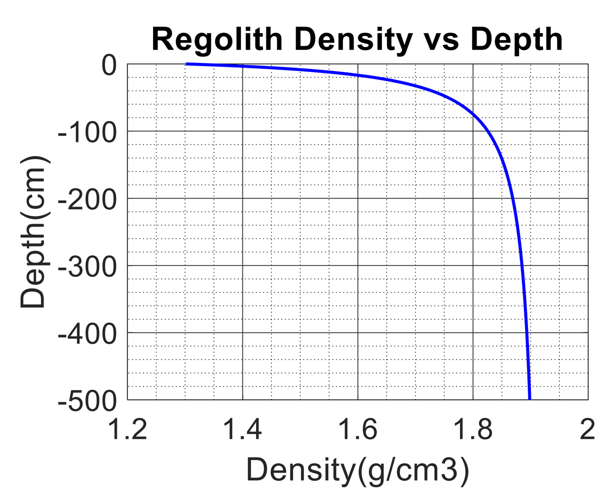

Figure 1. Lunar regolith density versus depth

Regolith Physical Temperature

$$T(z,t) = T_o + \Delta T_o \, e^{-z\sqrt{\omega/2\alpha}} \sin\left(\omega t - z\sqrt{\omega/2\alpha}\right)$$

where z and t are the depth and time, T_o is the mean surface temperature, ΔT_o and ω are the surface temperature fluctuation amplitude and frequency, and α is the thermal diffusivity [2].

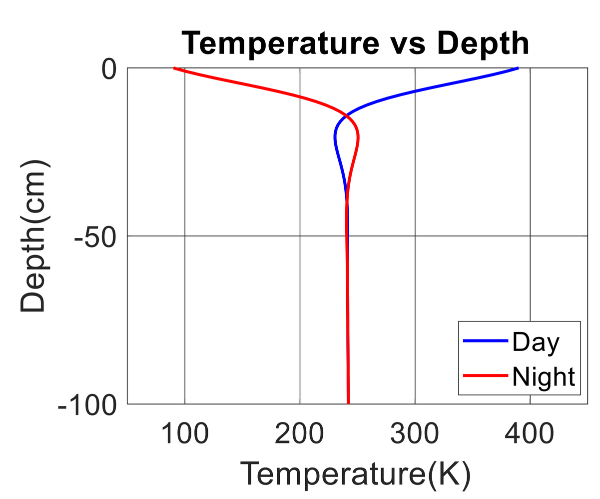

Figure 2. Lunar regolith temperature versus depth for lunar day and night.

Electrical Properties of the Regolith

$$\epsilon'(z) \approx 10^{0.27\rho(z)}$$

$$\epsilon''(f,z) \approx \epsilon'(z) \times 10^{(0.0272f+0.2967)\rho(z)+0.027p_{ch}-3.058}$$

where f is frequency in GHz and p_{ch} is the percentage of TiO_2 and FeO amount [3-4]. Using these models, and assuming the electromagnetic scattering is negligible in the regolith, we can approximately compute the normal incidence brightness temperatures at the regolith surface, $T_{Bs} = T_B(z=0,f)$, as:

$$T_{Bs} = \left(1 - R_{air-reg}\right) \times \left[\int_{z_{base}}^{z=0} \alpha(f,z) T(z) e^{-\int_{z'=z}^{z'=0} \alpha(z',f)dz'} dz + \left(1 - R_{reg-base}\right) T_{base}\, e^{-\int_{z_{base}}^{z=0} \alpha(z,f)dz}\right]$$

where $R_{air-reg}$ is the amplitude squared of the Fresnel reflection coefficient at the air-regolith boundary, $T(z)$ is the physical regolith temperature at depth z, $R_{reg-base}$ is the amplitude squared of the Fresnel reflection coefficient at the bedrock-regolith boundary, T_{base} is the physical temperature of the bedrock, and

$$\alpha(f,z) = -1 \times imag\left\{2\pi f\sqrt{\mu_o \epsilon_o\left(\epsilon'(z) - i\epsilon''(f,z)\right)}\right\}$$

is the electromagnetic attenuation coefficient in the regolith.

3. CHANG'E-1 AND CHANG'E-2 MISSIONS

Chang'E-1 and Chang'E-2 missions of the Chinese Lunar Exploration Program measured brightness temperatures of lunar surfaces via their nadir-looking microwave radiometers between 2007-2009 and 2010-2011, respectively. The measurements were done with four frequency channels at 3 GHz, 7.8 GHz, 19.35 GHz, and 37 GHz. Spatial resolution of the measurements were 50-35 km for Chang'E-1 and 25-17.5 km for Chang'E-2 due to different altitudes of the instruments.

4. SIMULATED VS MEASURED BRIGHTNESS TEMPERATURES

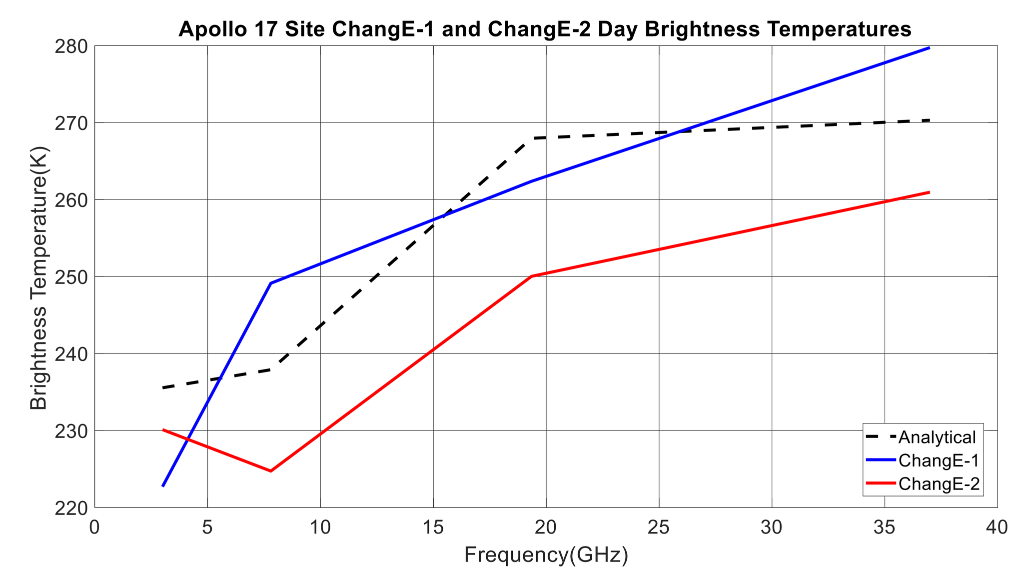

Figure 3. Average surface brightness temperatures measured by Chang'E-1 and Chang'E-2 over the Apollo 17 site during lunar days compared with the analytical calculations. Although the trends are similar, the differences between measured and simulated brightness temperatures can be as large as 20 K.

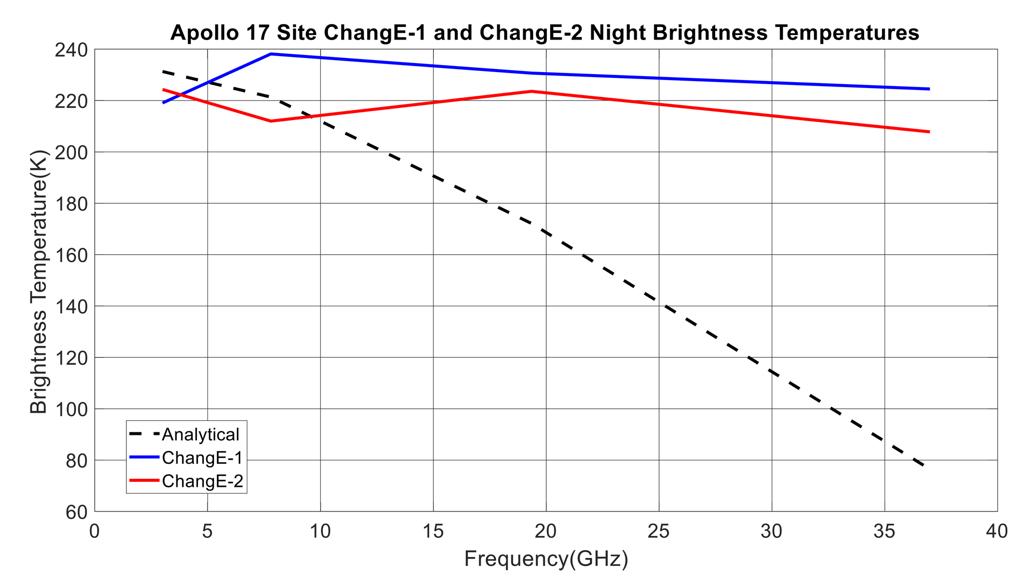

Figure 4. Average surface brightness temperatures measured by Chang'E-1 and Chang'E-2 over the Apollo 17 site during lunar nights compared with the analytical calculations. Simulated brightness temperatures are found to be much lower than the actual measurements at high frequencies which requires further investigations.

Electrical properties, i.e., complex permittivity, of the lunar regolith should be characterized over a wide range of temperatures and frequencies in the microwave spectrum with special emphasis on cold temperatures and high frequencies.

More comprehensive forward emission models are needed for accurate brightness temperature simulations.

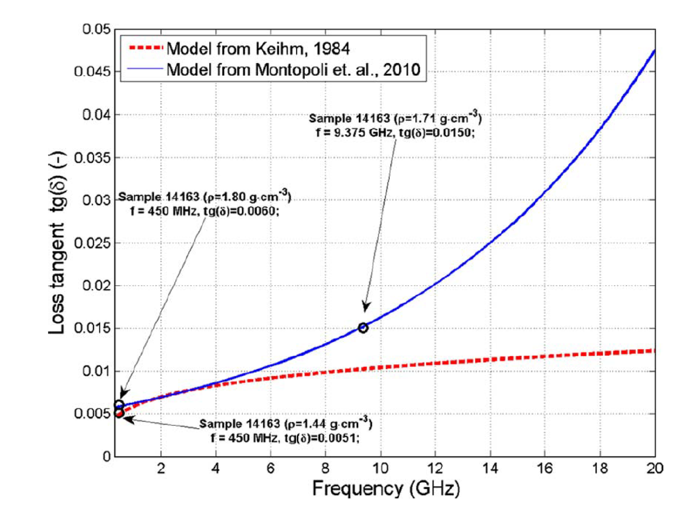

Figure 5. Electromagnetic loss tangent models for lunar regolith [4].

5. IMPORTANT OBSERVATIONS

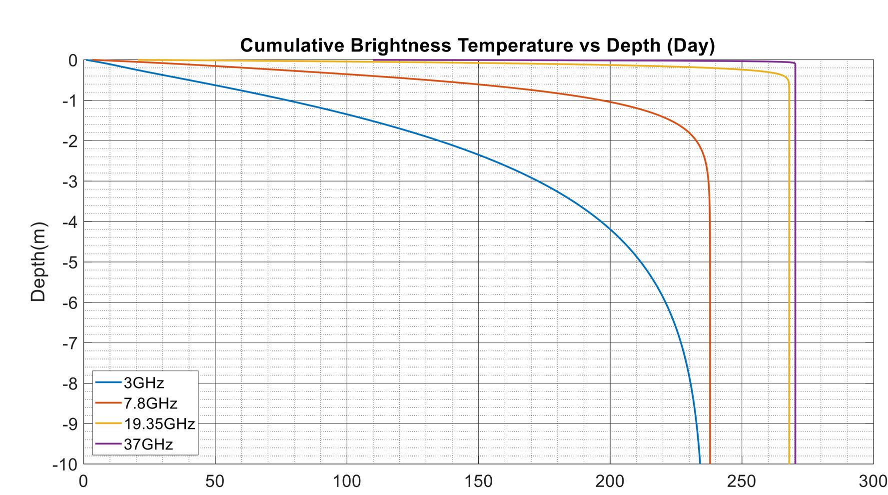

Figure 6. Cumulative brightness temperatures found by summing emissions from the surface to each depth at Chang'E-1 and Chang'E-2 frequencies. Notice that as frequency increases contributions from the deeper layers decreases. Higher frequencies are sensitive to only very shallow regolith.

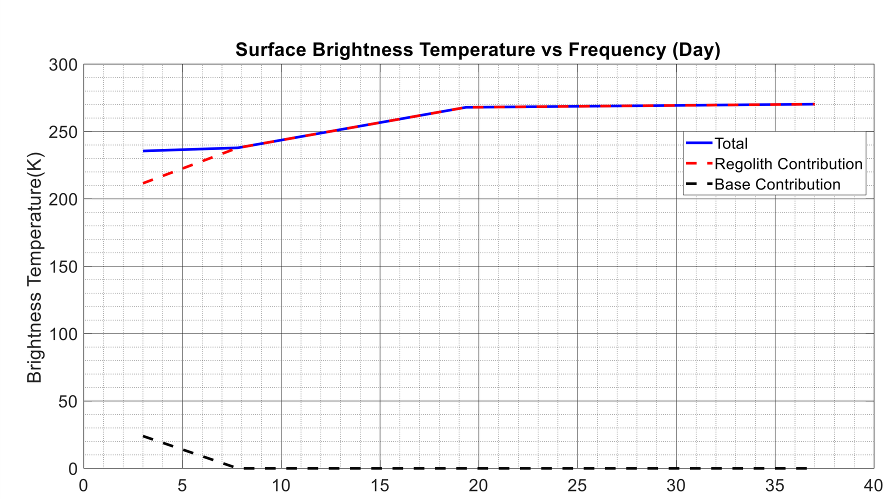

Figure 7. Surface brightness temperatures at Chang'E-1 and Chang'E-2 frequencies for a 5-meter regolith with rock base. Notice that brightness temperatures at low frequencies may be sensitive to the bedrock.

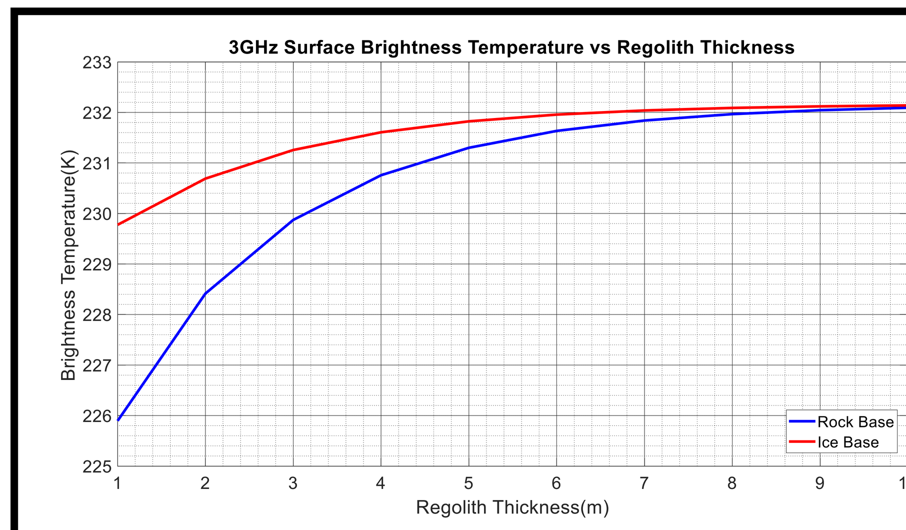

Figure 8. 3 GHz surface brightness temperatures computed for regolith on rock and ice bases versus the regolith thickness. Notice the significant impact of the bedrock type on surface brightness temperatures for thinner regolith.

Preliminary analyses have demonstrated that thermal, physical, and chemical properties of the lunar regolith and bedrock can be profiled versus depth via wideband microwave radiometry utilizing the considerable change in the electromagnetic penetration depth across the microwave spectrum.

However, first, more comprehensive forward microwave emission models should be developed to include volume scatterings, roughness of bedrock and regolith layers, density fluctuations within the regolith, coherent wave interferences, and temperature dependency of the regolith permittivity etc.

6. FUTURE WORK

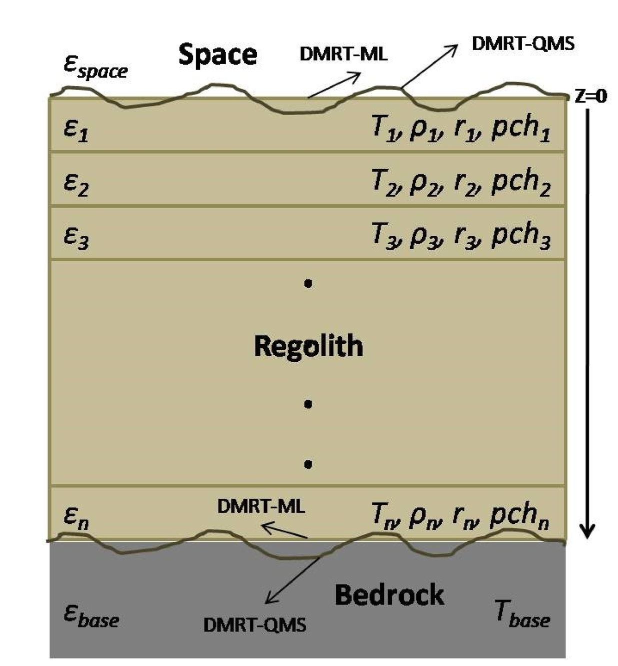

Figure 9. DMRT-ML and DMRT-QMS for lunar studies

The Dense Media Radiative Transfer – Multi Layers (DMRT-ML) and the Dense Media Radiative Transfer - QCA Mie scattering of Sticky spheres (DMRT-QMS) have been developed and widely used by Earth Science community to calculate surface brightness temperatures over ice sheets [5-6]. Ice sheets are considered as layered media and each layer is defined by its temperature, density, thickness and grain size. Then, using Rayleigh (DMRT-ML) or Mie (DMRT-QMS) scattering models, effective permittivity of each layer is computed and the surface brightness temperature is calculated as a function of incidence angle by solving the radiative transfer equation using the discrete ordinate method. DMRT-QMS, also takes surface and bedrock roughness into account using empirical models.

DMRT-ML and DMRT-QMS models (developed in Fortran and MATLAB, respectively and available to public) can be modified for lunar studies and used as more accurate forward microwave emission models for lunar regolith and bedrock.

Once a reliable forward emission model is established, numerical retrieval algorithms can be developed to retrieve the physical, thermal, and chemical properties of the lunar regolith and bedrock versus depth.

Figure 10. Recent developments in radiometer design and CubeSat technologies may enable future lunar missions which carry wideband microwave radiometers for passive remote sensing of lunar regolith and bedrock. The figure demonstrates the CubeRRT (CubeSat Radiometer RFI Technology Validation) instrument which carries a microwave radiometer operating in the 6-40 GHz band [7].

7. REFERENCES

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