CHARACTERIZATION OF LUNAR REGOLITH VIA PASSIVE REMOTE SENSING IN MICROWAVE SPECTRUM FROM 1 TO 10 GHZ

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Introduction: In this study, through a set of microwave radiation simulations, we have demonstrated that microwave radiometer measurements of lunar regolith at multiple frequencies from 1 to 10 GHz can be used to infer important regolith characteristics such as regolith thickness, internal temperature and density profiles, and chemical composition.

Regolith and Radiation Models: This study has been performed with following considerations regarding physical, thermal and electrical properties of lunar regolith, and electromagnetic radiation from regolith surface.

Regolith Density: Bulk density of lunar regolith, ρ is assumed to follow the expression described in [1] versus depth, z:

$$\rho(z) = \rho_d - (\rho_d - \rho_s)e^{-z/H} \tag{1}$$

where ρ_s is the surface density, H is the densification parameter, and ρ_d is the density at depths $z \gg H$. ρ_s and ρ_d are assumed to be 1.30 and 1.92 g/cm^3, respectively based on the Apollo measurements [2].

Regolith Temperature: Physical temperature, T, in lunar regolith versus depth, z, and time, t, is described by the solution of the following one-dimensional heat conduction equation (neglecting advection):

$$\rho(z)c(z,T)\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(k(z,T)\frac{\partial T}{\partial z}\right) + Q(z,T) \tag{2}$$

where $\rho(z)$, $c(z,T)$, $k(z,T)$, and $Q(z,T)$ are bulk density (g/cm^3), specific heat (Jg^{-1}K^{-1}), thermal conductivity (Js^{-1}K^{-1}cm^{-1}), and internal heat flux (Js^{-1}cm^{-2}), respectively. A numerical solution process for this equations is given in [3].

Regolith Complex Permittivity: The real part of the permittivity (ϵ') of lunar regolith has the following power law relation with the bulk regolith density [4]:

$$\epsilon'(z) \approx 10^{0.27\rho(z)} \tag{3}$$

On the other hand, the imaginary part of the relative permittivity (ϵ'') is expressed as a function of regolith density and chemical composition, p_{ch}(percentage of TiO_2+FeO amount), based on Apollo measurements and previous analyses with Chang'E-1 and 2 radiometer data [1,5]:

$$\epsilon''(z) \approx \epsilon'(z) \times 10^{0.038p_{ch}+0.312\rho(z)-3.260} \tag{4}$$

Electromagnetic Emission Model: The electromagnetic attenuation coefficient within the regolith can be computed for depth, z, and frequency, f, as [6]:

$$\alpha(f,z) = -2 \times imag\left\{2\pi f\sqrt{\mu_o\epsilon_o\left(\epsilon'(z) - i\epsilon''(z)\right)}\right\} \tag{5}$$

Then, assuming the electromagnetic scattering and internal reflections are negligible, normal incidence brightness temperatures at the regolith surface, $T_B(z=0,f)$ can be calculated as a function of frequency as:

$$T_B(z=0,f) = \int_{z_{deep}}^{z=0}\left[\prod_{z'=z}^{z'=0}\Gamma(f,z')\right]\alpha(f,z)\,T(z)e^{-\int_{z'=z}^{z'=0}\alpha(f,z)\,dz'}dz \tag{6}$$

where $\Gamma(f,z')$ and $T(z)$ are the amplitude squared of the Fresnel transmission coefficient between regolith layers at depth z' for frequency f and the physical regolith temperature at depth z, respectively.

Validation using Chang'E-1 Measurements: To validate the abovementioned models, Chang'E-1 brightness temperature measurements averaged over a 1º x 1º lat x lon grid around the Apollo 15 site are compared with the radiation simulations for a 4.4-meter regolith on a bedrock with permittivity $\epsilon' - i\epsilon''$ = 5.87 + 0.0086i which resemble the Apollo 15 site [7-8]. The amount of TiO_2+FeO and H are accepted as 5% and 10 cm, respectively. Solar incidence angle is taken as 130º.

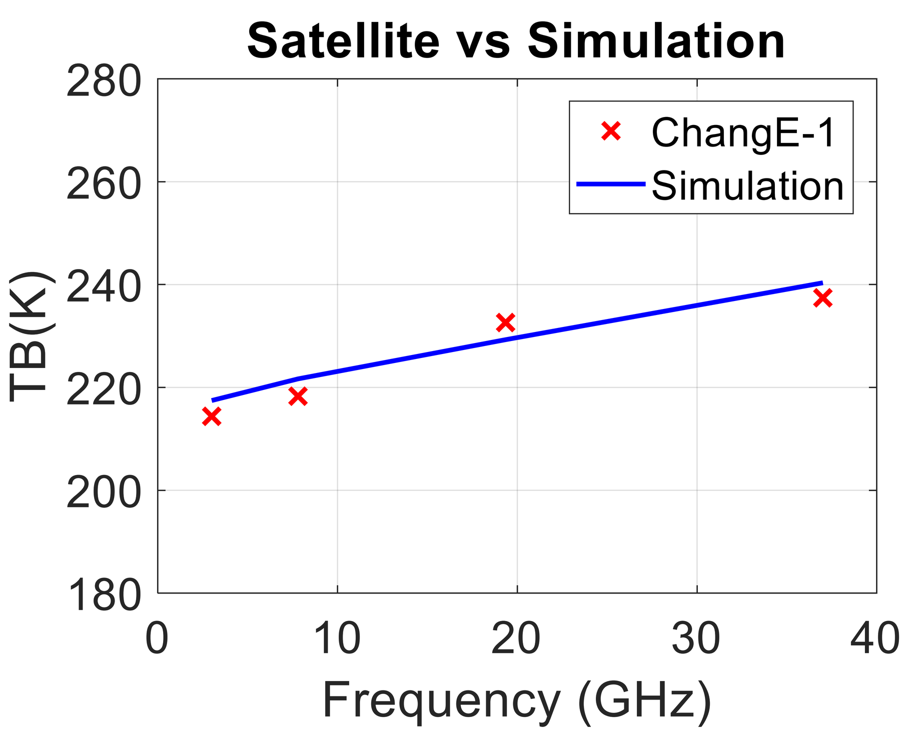

Fig. 1. Chang'E-1 measurements vs Simulations over the Apollo 15 site.

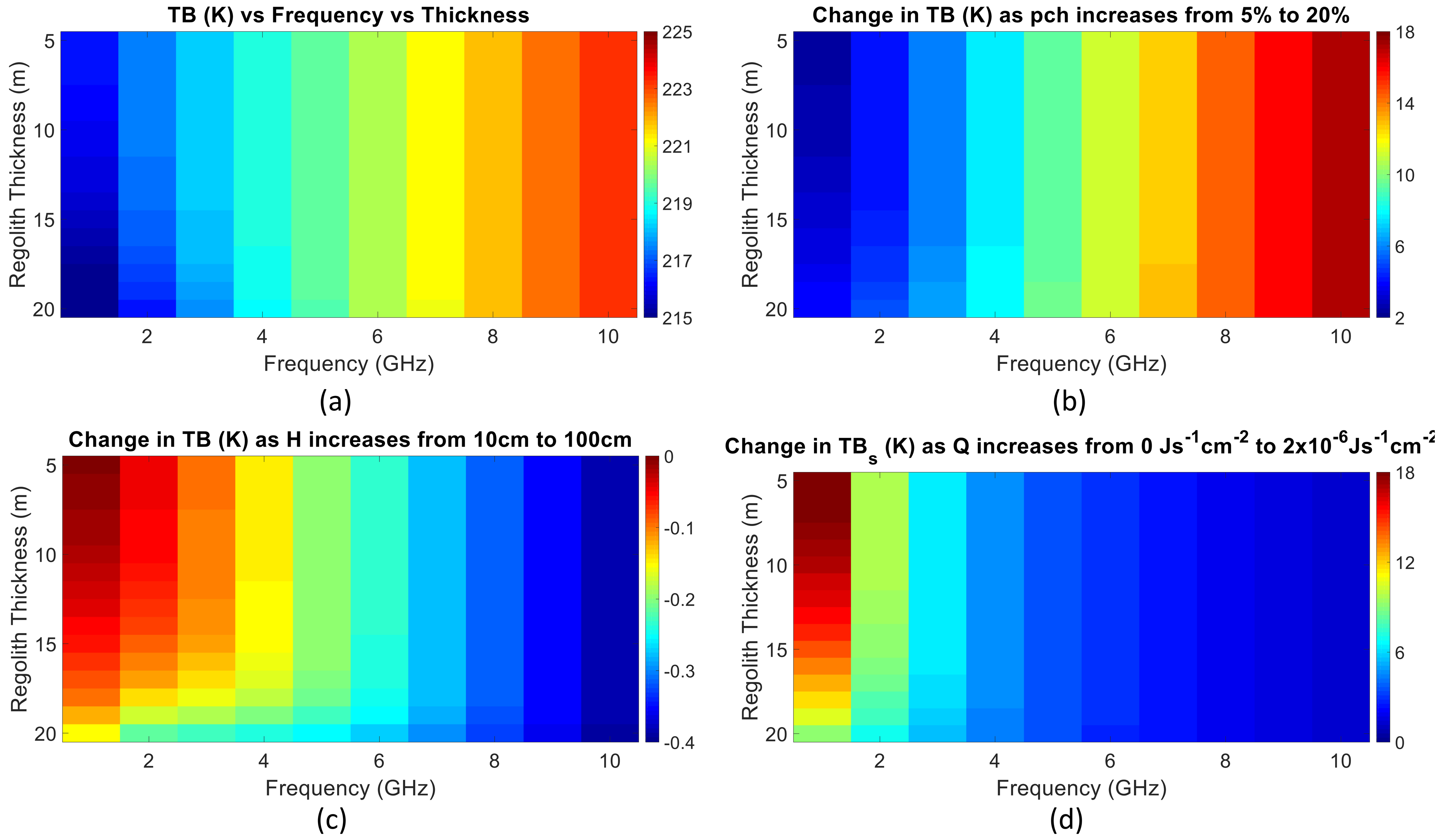

Fig. 2. (a) Surface brightness temperatures from 1 to 10 GHz for regolith thickness values between 5 and 20 meters, and changes as (b) p_{ch} varies from 5% to 20%, (c) H varies from 10 cm to 100 cm, (d) Q varies from 0 to 2×10^{-6} Js^{-1}cm^{-2}

Simulations and Results: Normal incidence surface brightness temperatures have been calculated at frequencies from 1 to 10 GHz for regolith thickness values between 5 and 20 meters as shown in Fig. 2(a) using the parameters used in the Apollo 15 site simulations.

➢Since electromagnetic penetration depth decreases with frequency, higher frequencies reflect warm shallow regolith and only brightness temperatures at lower frequencies are sensitive to changes in regolith thickness. For instance, brightness temperatures at 1 GHz decreases with thickness until 20 meters, whereas no significant change is observed at frequencies above 4 GHz as only upper regolith contributes to surface emissions at these frequencies. Thus, changes in brightness temperatures only at lower frequencies may imply changes in regolith thickness.

➢As shown in Fig. 2(b) increased p_{ch} to 20% leads to higher attenuation, thus shorter penetration depths. Therefore, brightness temperatures increase to reflect warmer regolith closer to the surface. The increase is more severe at higher frequencies, e.g., >15 K at 10 GHz vs <5 K at 1 GHz, as these frequencies are sensitive to layers near the surface where the temperature gradient is large. Thus, changes in brightness temperatures mainly at high frequencies may imply changes in chemical composition in the regolith.

➢Increase in H, on the other hand, results in less dense regolith and reduced attenuation; thus, brightness temperatures slightly decrease. Again, its impact, as seen from Fig. 2(c) , is more substantial at higher frequencies since the physical temperature gradient is larger in top layers.

➢Higher internal flux values increase the temperature rise with depth in deep regolith. Thus, larger Q values increase the surface brightness temperature, as shown in Fig. 2(d), mainly at low frequencies where deep regolith has a considerable contribution to the surface emissions. At large frequencies, e.g., >8 GHz, the impact is minimal.

Finally, it is important to recognize that the impacts of thermal, physical and chemical properties on the surface brightness temperatures shown here can be coupled rather than independent; thus, auxiliary information from other types of lunar measurements may be necessary to constrain retrieval studies for regolith characterization.

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