IMPACT OF WATER ICE PRESENCE IN LUNAR REGOLITH ON SURFACE BRIGHTNESS TEMPERATURES FROM 1 TO 10 GHZ. M. Aksoy[1], I. Walter[1], D. M. Hollibaugh Baker[2], J. R. Piepmeier[2], [1]University at Albany, State University of New York, 1400 Washington Ave, Albany, NY 12222, USA, maksoy@albany.edu, [2]NASA Goddard Space Flight Center, 8800 Greenbelt Rd, Greenbelt, MD 20771, USA, david.m.hollibaughbaker@nasa.gov.

Introduction: A high priority science and resource goal at the lunar surface is to determine the physical properties and volatile content of the regolith. One method of accomplishing this is through passive microwave radiometry, where measured brightness temperatures can be combined with models to constrain bulk regolith characteristics. Here, we focus on the ability of passive microwave radiometry to identify water ice in the regolith by, through a set of microwave radiation simulations, demonstrating the impact of the presence of water ice in regolith on microwave emissions from the lunar surface at frequencies from 1-10 GHz. For a favorable case where discrete ice layers are present, we consider a 10-cm thick ice layer at various depths in the lunar regolith. The simulations show that layers of water ice may lead to considerable changes in surface brightness temperatures within this frequency band, which is detectable by modern radiometer systems provided that the ice layer is close to surface where contributions of regolith layers to the surface emission are significant.

Theoretical Background: This study has been performed with the following considerations regarding physical, thermal and electrical properties of lunar regolith, and electromagnetic radiation from the regolith surface:

Regolith Stratigraphy: The lunar regolith is formed of different fragmented materials; thus, it is modeled as a planar layered medium where each layer may have different physical, chemical, and thermal properties. A 20 m regolith with 1 mm internal layers is considered in this study.

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

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

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], and H is accepted as 10 cm in this study. Fig. 1 shows the resulting regolith density versus depth.

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):

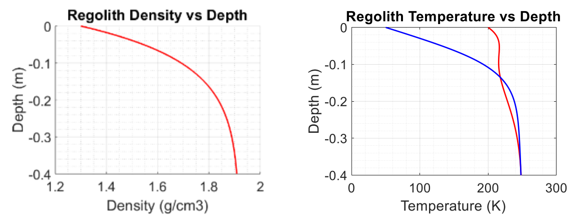

Fig. 1. Regolith density (left) and day (right red) and night temperature (right blue) profiles versus depth used in this study. Note that data are shown only for the top 40 cm of the 20 meter regolith. Deeper regolith is considered mostly isothermal.

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

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]. Lunar day and night regolith temperature profiles generated based on equation (2) for a region near lunar south pole (latitude 85^0 S) and used in this study are also shown in Fig. 1.

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

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

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]:

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

Electromagnetic Emission Model: Using the complex permittivity of lunar regolith, the electromagnetic attenuation coefficient can be computed for a specific depth, z, and frequency, f, as [6]:

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

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

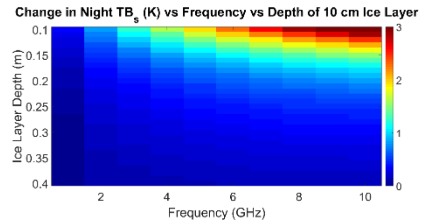

Fig. 2. Change in lunar surface brightness temperatures versus frequency and ice layer depth when a 10-cm ice layer is inserted into regolith during lunar night.

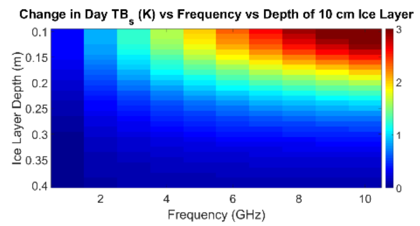

Fig. 3. Change in lunar surface brightness temperatures versus frequency and ice layer depth when a 10-cm ice layer is inserted into regolith during lunar day.

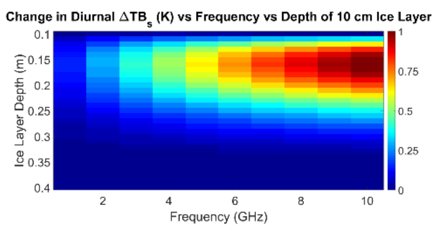

Fig. 4. Change in diurnal surface brightness temperature variations versus frequency and ice layer depth when a 10-cm ice layer is inserted into regolith.

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

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.

Simulations and Results: Normal incidence surface brightness temperatures have been calculated at frequencies from 1-10 GHz using equation (6) for a 20-meter regolith with density and temperature profiles given in Fig.1 and constant p_{ch} of 10%. The bedrock is accepted to be at the same temperature as the deepest regolith layer with complex permittivity of $5.87 + 0.0086i$, a value measured at the Apollo 15 site [7]. Then, an ice layer with 10 cm thickness and temperature equal to that of regolith at the same depth is inserted into regolith at various depths from 10 cm to 1 m, and changes in surface brightness temperatures have been analyzed to evaluate the feasibility of water ice detection in lunar regolith using microwave radiometry within the 1-10 GHz band.

Ice is electromagnetically more transparent than lunar regolith at frequencies from 1-10 GHz; thus, replacing regolith with ice at particular depth results in the loss of the contribution of that portion of the regolith to the surface emissions. On the other hand, due to the reduced path loss, regolith layers just below the ice layer contribute considerably more to the surface emissions. This effect can be seen in Figs. 2 and 3 which demonstrate the change in surface brightness temperatures due to the insertion of the 10 cm ice layer versus the depth of the ice layer and frequency during the lunar night and day. Replacing regolith with ice at depths between 0.1 and 0.15 m leads to significant (>2 K) increases in surface brightness temperatures especially at frequencies above 3 GHz as the main contribution to the surface emissions at these frequencies originate from layers at around ~0.15 m depth. Thus, brightness temperature increases due to reduced path loss for emissions from these regolith layers surpass the loss of emissions due to the ice layer itself. At low frequencies, however, the surface emission is the sum of small contributions from regolith layers across a wide depth range due to larger electromagnetic penetration depths, thus replacing regolith layers with ice does not have a significant impact. Likewise, inserting ice layers in deep regolith does not change surface emission considerably as the contribution of these layers to the surface emission is limited at all frequencies. Finally, it can be observed that the impact of the water ice presence in regolith is stronger during the lunar day; thus, as seen in Fig. 4, diurnal changes in surface brightness temperatures also demonstrate up to 1 K increases at higher frequencies for ice layers buried at 0.1-0.2 m depth.

As a result, initial analyses presented in this paper indicate that it may be possible to detect the presence of water ice layers in near-surface regolith using microwave radiometer systems operating within the 1-10 GHz band, provided that enough auxiliary information regarding physical, chemical and thermal properties of the regolith is available.

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