MICROWAVE REMOTE SENSING OF LUNAR SUBSURFACE TEMPERATURES: RECONCILING CHANG’E MRM AND LRO DIVINER.

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Introduction: Microwave remote sensing measurements have the potential to reveal temperatures as a function of depth on regolith covered bodies [1]. This could be a new tool for examining the subsurface of the Moon and other solid surface solar system bodies. Much as has been used for atmospheric remote sensing (e.g. the Juno MWR instrument), passive microwave brightness temperatures of solid surfaces provide information on temperatures as a function of depth. However, the correlation of brightness temperature and physical temperature is not straight forward. Material properties (namely ilmenite content and density) control the depth from which the thermal emission originates.

Data: New lunar orbital data has opened a new opportunity to measure lunar heat flux from ground based radio wavelength measurements. By combining Chang’E 1 and 2 microwave remote sensing measurements with thermal and compositional properties data from the Lunar Reconnaissance Orbiter (LRO), Lunar Prospector (LP) and other missions, we can begin to constrain the depth from which the heat is coming- creating a more detailed understanding of the temperatures below the lunar surface. Ideally, this can be used to detect subsurface density anomalies (rocks or ice), find areas with unique dielectric properties (again, rocks or ice), and potentially constrain geothermal heat flow.

The Chang’E 1 and 2 MRM (microwave radiometer) instruments were nearly identical 4-channel radiometers. They observed the Moon passively at 3.0, 7.8, 19 and 37 GHz (~10, 7, 1.5 and 0.8 cm). For average lunar regolith densities, most radiation received by a particular radiometer will come from ~10x the observation wavelength. Therefore, the shortest wavelength Chang’E channel (37 GHz) should be dominated by regolith temperatures in the upper ~10 cm of the Moon, while the longest (3 GHz) channel may see a meter or more.

Model: Here we present efforts to provide a model of subsurface regolith temperatures that are consistent with both LRO Diviner surface temperature measurements and the Chang’E MRM data. While daytime lunar surface temperatures are roughly in equilibrium with the sun, nighttime surface temperatures will be dominated by upwelling heat from the upper ~20cm of the lunar regolith. Vasavada et al. [2] and Hayne et al. [3] found that other than anomalous crater rays, most of the Moon can be described with a simple exponentially increasing density over the upper 10’s of cm. Therefore, most variation in the Chang’E MRM data should be coming from physical temperature differences and compositional changes. In Figure 1, we can see the dominance of physical temperature as a function of latitude.

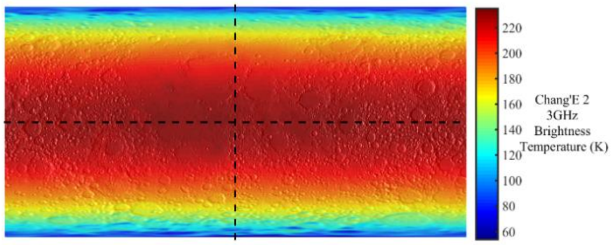

Figure 1: Time averaged Chang’E 2 data at 3.0 GHz showing the dominance of physical temperature on the radiometer singnal.

Figure 2 illustrates the same data, but with the latitudinally averaged 3GHz brightness temperature removed. This “residual” map shows the second-order dominance of composition (and topographic effects on temperatures nearer the poles). The iliminite-rich Procellarum KREEP Terrain (PKT) is clearly visible. However, this enhanced “residual” is not perfectly correlated with known compositional variations (from Lunar Prospector GRS, Clemintine multispectral, LRO, etc data). Results of the LRO Diviner global topographic thermal model [e.g. 4] can be used to remove some of the topographic “noise” seen in this residual map.

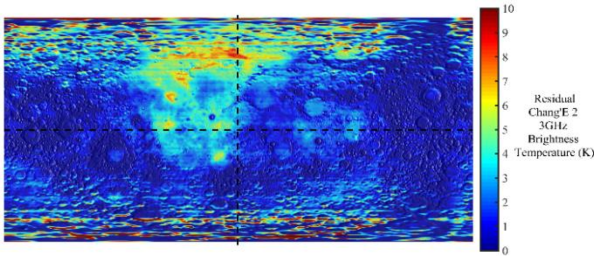

Figure 2: 3GHz residual time averaged brightness temperature once latitudinal average brightness temperature has been removed.

By fitting regions with known electrical properties (such as the ilmenite poor lunar highlands) and LRO Diviner-constrained regolith density profiles, we can constrain the “weighting function”, or contribution to the total microwave brightness temperature as a function of depth, of any given MRM channel. We can then use our Diviner-constrained forward thermal model to produce a model of expected brightness temperature at a specific location. Variations from that nominal forward model value potentially highlight either an anomalous density (rock or ice) or an anomalously high geothermal heat flux.

The weighting function of a given wavelength channel will determine the depth from which thermal radiation is originating. For a given location (and therefor density and measured composition) and model temperature profile, our model weighting function is calculated as:

$$w_i = (1-s_i)\cdot(1-e^{-2k_i d_i})\cdot(1+\left|R_{i(i+1)}\right|^2\cdot e^{-2k_i d_i})\cdot\prod_{j=0}^{i-1}((1-\left|R_{j(j+1)}\right|^2)\cdot e^{-2k_j d_j})$$

Where w_i is the weight coefficient of layer i, S_i is the single scattering albedo in layer i, k_i is the absorption coefficient of layer i:

$$k_i = 2\pi\frac{f}{c}\sqrt{\varepsilon}\tan\delta$$

where *tan* δ is the material loss tangent, which is dependent primarily of the ilmenite (Ti and Fe) content of the regolith. Microwave brightness temperature can be calculated by multiplying wi by the model calculated physical temperature profile: $T_b(\lambda) = \sum wi(\lambda)T(z)dz$.

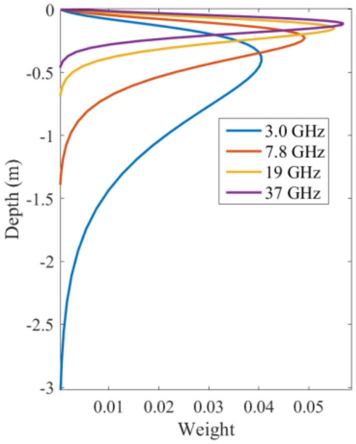

Figure 3: Example of weighting functions for the 4-channel Chang'E MRM radiometers for average highlands composition.

The main variation spatially is the material loss tangent. [5] and [6] found the loss tangent could be modeled as:

$$\tan\delta = 10^{(a1(f)+a2)\rho(z)+bS-c}$$

With fits a1=0.0272, a2=0.2967, b=0.027, c=3.058. We are working to confirm these fit parameters with the MRM data.

Ri(i+1) is the reflection coefficient between layer i and layer i+1:

$$R_{i(i+1)} = \frac{\sqrt{\varepsilon_{i+1}}-\sqrt{\varepsilon_i}}{\sqrt{\varepsilon_{i+1}}+\sqrt{\varepsilon_i}}$$

Using a layered approximation at the same 5mm layer resolution as our LRO Diviner-based thermal model, we will produce a full radiative transfer model of $T_b(\lambda)$ as in [7]. Modeled temperature profiles and microwave radiation can then be coupled to provide a forward model for brightness temperature at any wavelength at any geothermal heat flux that can be best fit to multi-wavelength microwave data.

Changes in geothermal heat flux can be iterated to obtain a best fit with the microwave radiometer data. These can be calibrated to the Apollo 15 and 17 HFE data. As geothermal heat will have little effect on surface temperatures [8]) variations in heat flux can be safely approximated by superimposing a gradient ***dT/dz=q/k*(*z*)**, where ***q*** is seeded with the local heat flux from a model based on Lunar Prospector Gamma Ray Spectrometer Thorium measurements.

This modelling effort has also shed light on constraining likely calibration issues within the Chang'E MRM data. Non-physical Tb variations can be found spotted when compared to model output. The primary calibration issues appear to be due to instrument heating while the Chang'E spacecraft was in a terminator orbit (6am, 6pm). We now believe that with proper recalibration, these data can be recovered to create a fully consistent dataset.

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