DERIVING LUNAR LOSS TANGENT AND SUBSURFACE TEMPERATURES FROM CHANG'E-2 MRM AND LRO DIVINER. M. A. Siegler[1], J. Feng[1], P. Lucey[2], P. O. Hayne[3], D. Blewett[4], J. Cahill[4], [1]Planetary Science Institute (1700 East Fort Lowell, Suite 106 Tucson, AZ 85719-2395, jfeng@psi.edu), [2]University of Hawaii, [3]University of Colorado, Boulder, [4]Johns Hopkins Applied Physics Lab.

Introduction: The microwave brightness temperature of an object depends on the physical temperature and the material properties of the medium being measured. Measurements from the Lunar Reconnaissance Orbiter Diviner Lunar Radiometer have dramatically advanced our understanding of lunar physical temperatures [e.g 1]. Meanwhile, the Chang'E (CE) 1 and 2 Microwave Radiometer (MRM) instruments mapped the Moon at microwave wavelengths (3.0, 7.8, 19.35, and 37GHz) for the first time [2]. Using these two data sets in conjunction, we can open a new window into the dielectric properties and subsurface temperatures of the shallow lunar subsurface.

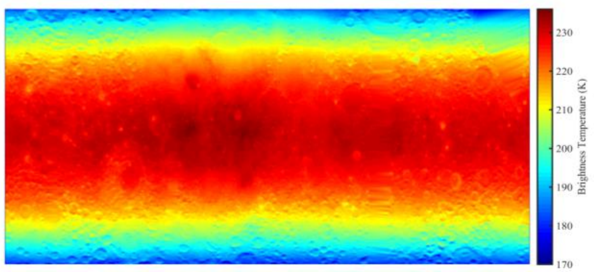

Figure 1: Global measurements at midnight from Chang'E-2 microwave radiometer's 3GHz channel.

A global map of midnight brightness temperatures from the 3 GHz channel is shown in **Fig 1** and indicates that microwave T_b follows, to first order, physical, subsurface temperatures. These measurements have been used to reconstruct regolith thickness [3], dielectric properties [4], subsurface temperatures [5], and geothermal heat flow [6].

Dielectric properties (by which we primarily mean the real, ε, and imaginary, ε', dielectric constants) of minerals and the presence of rocks (or ice) control the transmission of electromagnetic waves through the regolith layers that cover bodies like the Moon and Mars. Dielectric properties have a large impact on radar observations of planetary surfaces as they control radar surface reflections and the depth to which radar penetrates [7,8]. However, it is difficult to measure dielectric properties with radar without a reflector at a known depth.

Dielectric properties are also of great interest for their ability to map mineral variations and the presence of rocks. Earth-orbiting microwave radiometers such as SMAP [9,10] use the dielectric contrast between soil and liquid water to map subsurface moisture. Lacking liquid water, the primary mineral affecting the dielectric properties of the lunar regolith is believed to be ilmenite (Fe, Mn, Mg, or Ni + TiO_3).

Ilmenite titanites have a high dielectric loss due to the isolation of TiO_6 octahedra by the Fe, Mn, Mg, or Ni O_6 layers and a cation vacancy layer [11] which allows the cation to be highly mobile and absorb energy at microwave frequencies. This mineral is also of interest because ilmenite should retain implanted solar-wind ^{3}He more efficiently than other minerals [12,13] and may play a large role in future resource utilization of the Moon. Subsurface water ice on the Moon and Mars has a much smaller dielectric contrast with dry regolith than does liquid water [7], so ice would not cause a huge change in absorption as is used on Earth, but would be seen primarily as a pore-filling material, with a weaker, but measureable dielectric contrast to vacuum-filled pores and through changes in thermal properties.

The real, ε, and imaginary, ε', dielectric constants are often combined as the "loss tangent". Heiken et al. [14] found the loss tangent (tan Δ at frequency, f) could be modeled as:

$$tan\,\Delta = \frac{4\pi\varepsilon}{\varepsilon' f} = 10^{(a1(f)+a2)\rho(z)+bS-c} \quad (1)$$

where *a1*, *a2*, *b*, and *c* are fit coefficients. The nomenclature follows Montopoli et al. [15] who found a1=0.0272, a2=0.2967, b=0.027, c=3.058 using laboratory data, with the loss tangent varying between 4.5×10^{-3} and 1.5×10^{-2} dependent on regolith density (solid water ice is similar with a loss tangent of ~4.1×10^{-3} [Paillou et al., 2008]). $\rho(z)$ is density as a function of depth, *z*, and *S* is the weight % value of Ti plus Fe. Fa and Wieczorek [16] found a much stronger correlation with mapped Ti than Fe, which is supported by our own analysis here.

Increasing the loss tangent will decrease the depth from which emitted radiation can be seen. The proportion of radiation emitted from a certain depth can be characterized by a "weighting function" $w(z)=T_b(z)/T(z)$, where the microwave brightness temperature T_b is calculated:

$$T_b(\lambda) = \left(1 - R_\lambda(\theta)\right)\sec\theta \int_0^\infty \kappa_\lambda(z)\rho(z)T(z) \times \exp\left[-\int_0^z (\kappa_\lambda(z')\rho(z')\sec\theta\, dz'\right] \quad (2)$$

where $\kappa_\lambda(z) = \frac{2\pi}{\lambda}\sqrt{\epsilon'}\tan\Delta$ for wavelength λ=c/f. R_λ is the surface reflectivity (1- R_λ is the microwave emissivity) at wavelength λ, and $\kappa_\lambda(z)$ is the absorption coefficient and ρ(z) is density as a function of depth.

The Density, $\rho(z)$, of the upper 20cm is well constrained by LRO Diviner [17], and globally by Hayne et al. [18]. Accounting for polarization, R (which has a perpendicular and parallel polarized component that depends on observation angle, θ) is obtained:

$$R_\lambda(\theta) = \frac{1}{2}R_\perp(\theta) + \frac{1}{2}R_\parallel(\theta) = \left|\frac{(1-\sqrt{\epsilon'})}{(1+\sqrt{\epsilon'})}\right|^2 \quad (3)$$

and the absorption coefficient. As the Chang'E instrument was nadir viewing, polarization was far less important than it is for Earth-viewing geometries.

As the loss tangent controls the depth from which observed radiation is emitted, and temperature amplitude decreases with depth (Fig 2a), an area with a lower loss tangent will show smaller diurnal variations (deeper thermal emissions) in brightness temperature. This can be seen clearly in a map of CE-2 MRM brightness temperature diurnal amplitude (Figure 3a) as compared to LROC derived titanium (Figure 3b, [19]). Here, titanium increases in the loss tangent lead to larger brightness temperature amplitude.

We can use the LROC data in combination with the MRM to re-derive the dependence of the loss tangent on titanium (shown in Fig 2d). We preliminarily find an updated fit for Equation 1 with $a1$=-0.05, $a2$=0.0, b=0.022, c=2.07. Using the absolute value of the data in the 37 and 19 Ghz channels, we find a single scattering albedo of 0.036. The 3.0 and 7.8 Ghz absolute calibration requires a shift by 18 and 14K, respectively. Such shifts are likely due to calibration horn antenna contamination and these channels are being recalibrated (discussed in Feng et al., this meeting).

Using this model, we can now derive the weighting functions of each frequency as a function of titanium content. This allows the MRM data to be compared to physical temperature as predicted by subsurface thermal models. Variations in temperature from this predicted model are due to buried rocks, subsurface titanium (not seen by LROC), or due to anomalous temperature variations at depth (geothermal heat flux).

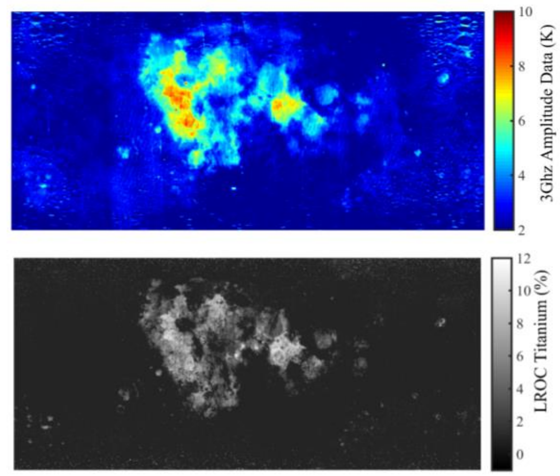

Figure 3: (a) diurnal amplitude of CE 2 MRM 3Ghz data (b) Sato et al. [19] LROC-derived Titanium %.

References: [1 Williams et al. (2018) JGR. [2] Zheng et al., (2012) [3] Fa and Jin (2012) [4] Gong, et al. (2015) [5] Hu, et al. (2017) [6] Siegler and Feng (2017) [7] Paillou et al. (2008) [8] Ulaby et al. (1982) [9] Entekhabi et al. (2010) [10] Chan et al. (2016) [11] Sohn et al. (1994) [12] Johnson et al. (1999) [13] Taylor (1994) [14] Heiken et al (1991) [15] Montopoli et al. (2011) [16] Fa and Wieczorek (2012) [17] Vasavada et al. (2012) [18] Hayne et al. (2017) [19] Sato et al. (2017)

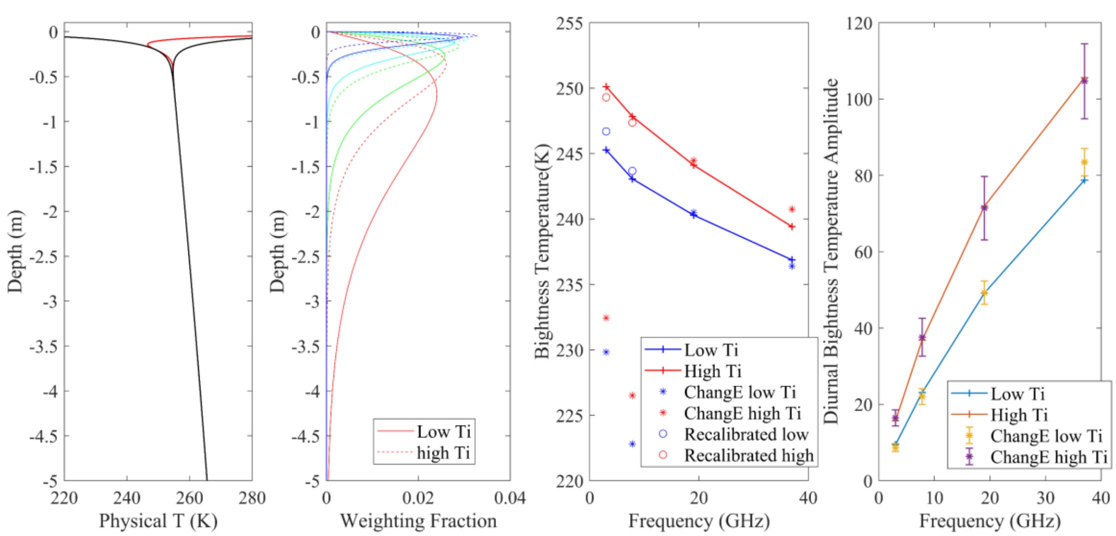

Figure 2: (a) Modeled physical temperatures with 10mW/m² heat flux (b) weighting functions for the Chang'E channels (with 0%, low, or 12%, high, Ti) (c) Data and model Tb vs frequency with recalibration (Siegler and Feng, in process of 7.8 and 3Ghz data- note recalibration does not affect the relative value or amplitude, just absolute value, so does not affect the loss tangent fit) (d) Data and model diurnal amplitude vs frequency with Chang'E data shown as used to fit an updated loss tangent.