Science Case for Microwave Wavelength Measurements -Authors: Matthew Siegler, Jianqing Feng **Cosigners:** William Blackwell, David Blewett, Shannon Brown, Bryan Butler, Joshua Cahill, Simon Dicker, Adrienne Dove, Rebecca Ghent, Timothy Glotch, Paul Hayne, Karl Hibbits, James Keane, Stephen Keihm, Paul Lucey, Sidharth Misra, David Paige, Than Putzig,Edgard G. Rivera-Valentín, Christopher Ruf, Isaac Smith, Adrian Tang

Executive summary Microwave radiometer can provide a powerful tool for examining the temperatures, dielectric, and physical properties of surfaces and subsurfaces of solid bodies in our Solar System. Any body will emit microwave radiation proportionate to its physical temperature and the dielectric properties of material overlying it. Therefore microwave emission from a body can be used to reconstruct information about shallow (upper ~10m) physical temperature and material properties, with sensing depth depending on the wavelength and material. These information include the presence of surface and subsurface density anomalies (e.g., rocks and ice), dielectric properties due to composition, thermal properties, and deep physical temperatures (due to changes in geothermal heat flux). Here we summarize the state of the knowledge and potential abilities of such instruments.

Introduction *The Artemis polar missions will aim to measure subsurface composition and search for the presence of subsurface ice, which lends to science goals that can be addressed with microwave (~300MHz - 300GHz) remote sensing.* Longer wavelength, *passive* microwave remote sensing shows promise to reveal new information about the subsurface physical properties and thermal state of the upper 10s of meters of solid bodies. This is separate and complementary to the information about planetary subsurface obtained by *active* microwave-wavelength radar. Passive microwave instruments look at thermal radiation emitted from the subsurface material itself. These instruments are traditionally used for atmospheric (e.g., Mariner 2 Venus; JUNO MWR, Janssen et al., 2017; Rosetta MIRO, Gulkis et al., 2007) and Earth orbiting sea surface observations (e.g., Jason, Topex).

For solid-surface planetary bodies, transparency of a surface at microwave wavelengths varies mainly due to changes in mineralogy (e.g., ilmenite) and density (e.g., subsurface bedrock). Physical temperatures vary mainly with regolith thermal inertia (influenced by the presence of subsurface rocks or ice) and, at appropriate wavelengths, geothermal heat. Here we summarize the case that a microwave radiometry and spectroscopy on the surface or orbiting the Moon (or any solid body) could measure: 1) dielectric properties, 2) presence of bedrock, buried rocks and ground ice, and 3) subsurface temperatures that would constrain geothermal heat flow.

An object's microwave brightness temperature is a function of its physical temperature and its frequency-dependent dielectric loss, often summarized as the *loss tangent*. The loss tangent is the ratio between the real (ε') and imaginary (ε'') dielectric constants, (ε''/ε'). The real part (ε') controls the speed of the electromagnetic waves, and the imaginary part (ε'') controls energy attenuation; and the loss tangent determines the total energy lost in the medium. The loss tangent on the Moon, for example, is dominantly controlled by the distribution of the dielectrically lossy mineral ilmenite and the presence of rocks.

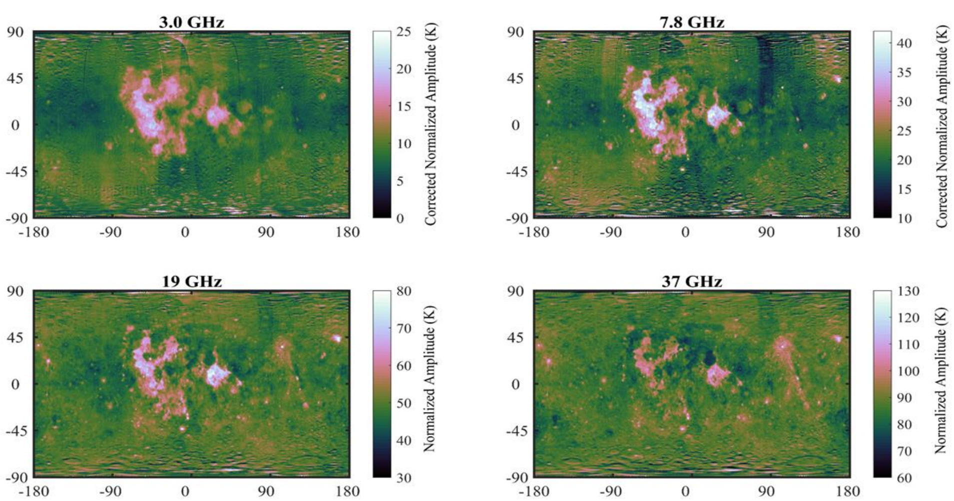

Figure 1. Global brightness temperature amplitudes at all Chang'E-2 frequencies after a time of day correction and latitudinal normalization plotted at ¼ degree resolution.

Figure 1 shows data from the Chang'E-2 MRM instrument, the best example that exists of a microwave radiometer measurement of a solid surface body. Here we see globally fit microwave diurnal amplitudes at each of the four Chang'E MRM frequencies (normalized to equatorial amplitude, Siegler et al., 2020). From its orbit, approximately 100 km above the lunar surface, the CE-2 data have channel-dependent resolutions around 17.5-25 km (Hu et al., 2017; Feng et al., 2020), depending on frequency. These measurements have been used to reconstruct regolith thickness (Fa and Jin, 2010), dielectric properties (Gong, et al., 2015; Feng et al., 2020), subsurface temperatures (Hu et al., 2017), and geothermal heat flow (e.g. Siegler and Feng, 2017).

One can readily see that features known to be rocky (e.g. Bandfield et al., 2011) and titanium rich (Lucey et al., 2000; Sato et al., 2017). For example, areas with large diurnal amplitude include the rocky rays of Giordano Bruno in the (19 and 37-GHz maps), and high-TiO_2 Mare Tranquillitatis (in all four maps). These data show that microwave observations of a body like the Moon can clearly reveal both physical properties and composition of near-surface materials. These observations can greatly enhance the science return of other measured quantities (such as infrared surface temperatures, visible mapping of rocks, through infrared spectral measurements of composition).

Top Level Science Microwave radiance is typically measured as brightness temperature (with units of K). Microwave brightness temperature, T_b, is effectively the integrated physical temperature of a material over a given depth weighted by the dielectric loss of that material. It is related to physical temperature, T, as $T_b = \int_0^\infty w(z)T(z)dz$, where w is the microwave weighting function.

The weighting function characterizes depths from which radiation emitted in the microwave arises. **Figure 2a** illustrates a modeled subsurface temperature profile for the lunar equator. The amplitude of physical diurnal temperature amplitude decreases exponentially with depth. Therefore, weighting functions (examples in **Fig. 2b**) with peak weights deeper in the regolith will result in smaller diurnal brightness temperature amplitudes. In the case of typical lunar material, low-frequency data (less than ~1 GHz) will sound deep enough that it will be nearly constant with time. **Fig. 2b**, shows examples of calculated microwave weighting functions at 19 and 37 GHz (Chang'E MRM frequencies) for average low TiO_2 highlands and high TiO_2 mare. In **Fig 2c**, we plot the resulting microwave brightness temperatures for the weighting functions in **Fig 2b** as a function of lunar local time. Here we see diurnal amplitude and absolute brightness temperature value can serve as a probe of the subsurface compositional and physical structure and temperature of the regolith with depth.

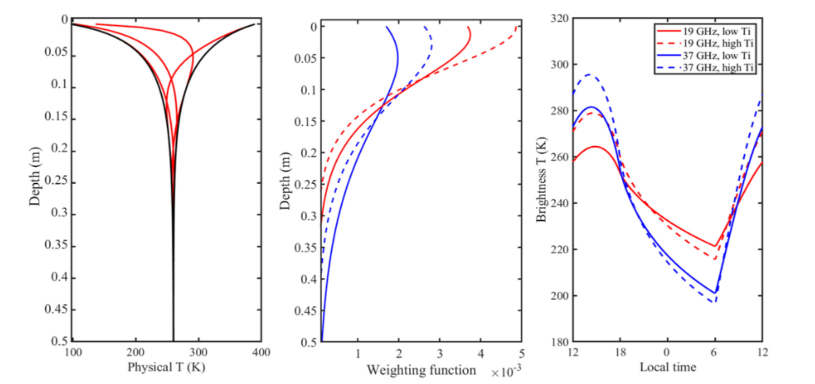

Figure 2. (a) Equatorial physical temperature model (black is max/min, red for every 6 hours) and illustrations of the approximate effects of frequency and ilmenite (low=1%, high =10% weight fraction TiO_2) on (b) the microwave weighting function and (c) modeled diurnal brightness temperatures.

Relevance to Artemis objectives Microwave radiometry/spectroscopy has the potential to reveal new information about the near surface composition (regolith density, thermal and dielectric properties), bulk internal properties (though a constraint on geothermal heat flow), and likely the presence and location of subsurface volatiles (again through dielectric, thermal, and density variations). A microwave instrument on a polar orbiter could provide reconnaissance maps of subsurface density, temperature and dielectric properties that could direct landed missions towards ice. On the surface, a landed or rover-based microwave radiometer could perform complementary work to a ground penetrating radar (GPR) and infrared measurements allowing for a unique subsurface characterization of thermal and dielectric properties, which should be diagnostic of rock and ice depth as well as local geothermal heat flux. This will greatly aid ISRU characterization and lower reliance on physically drilling to depth.

References [1] Bandfield et al., (2011) JGR, *116*(E12). [2]Cahill, (2014) *Icarus*, *243*, 173-190. [3] Fa, W., & Jin, Y. Q. (2010) *Icarus*, *207*(2), 605-615. [4] Feng J. Siegler, M. A., Hayne, P.O., (2020) JGR Planets, doi: 10.1029/2019JE006130 [5] Glotch et al., 2020 (Decadal White Paper) [5] Gong, X., Paige, D. A., Siegler, M. A., & Jin, Y. Q. (2014) *IEEE Geoscience and Remote Sensing Letters*, *12*(2) [6] Gulkis, et al. (2007) *Space Science Reviews*, *128*(1-4), 561-597. [7] Hu, et al. (2017). *Icarus*, *294*, 72-80. [8] Keihm, S. J. (1984). *Icarus*, *60*(3), 568-589. [9] Lucey, et al., (2000) *JGR: Planets*, *105*(E8). [10] Sato, et al. (2017) *Icarus*, *296*, 216-238. [11] Jannsen et al. (2017) *Space Science Reviews*, 1-47. [12] Piddington, J. H., & Minnett, H. C. (1949) *Australian Journal of Chemistry*, *2*(1), 63-77. Siegler, M.A., J Feng (2020) JGR Planets [13] Zhenget al. (2012) *Icarus*, *219*(1), 194-210.