Science Case for Microwave Wavelength Measurements

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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 warm 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 uppermost millimeters of solid Solar System bodies have received the lion's share of attention in the first ~7 decades of planetary exploration. We anticipate the next decade will see a large advance towards measurements of the subsurface, which lends to science goals that can be addressed with microwave (~300 MHz - 300 GHz) remote sensing. Longer wavelength data, passive microwave remote sensing shows promise to reveal new information about the subsurface physical properties and thermal state of the upper tens 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; the Rosetta MIRO instrument, Gulkis et al., 2007) and Earth orbiting sea surface observations (e.g., Jason, Topex) and more recently sea-ice observations (e.g., AMSR-2; Keller et al., 2020).

The first global microwave observations of a solid body were that of the Moon, made by the Chinese Chang'E (CE) 1 and 2 missions (**Figure 1**). The Microwave RadioMeters (MRM, also commonly called Chang'E Lunar Microwave Sounder, CELMS) made measurements at four frequencies (3.0, 7.8, 19.35, and 37 GHz; or equivalently 10, 3.8, 1.6 and 0.8 cm wavelengths; Zheng et al., 2012). 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). The Chang'E data unfortunately suffer from calibration issues and the fact that frequencies chosen due to existing technology and not science goals.

Figure 1: Lunar near-side brightness temperature from CE-2 MRM 37GHz at “noon” (data from 12:30 to 14:30 are used for this figure) to show the high quality of data available. Note the appearance of high-titanium mare (such as mare Tranquillitatis) as hotter, which results from shallow, warmer emission.

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, Mars or other 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. Despite the potential this capability promises, no NASA passive microwave instrument has explored another body for subsurface measurements. Even Earth observing instruments have hailed from Japan and ESA. Preliminary data from the Chang'E 1 and 2 orbiters have provided a look into the potential of such instruments.

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.

Microwave instruments are platform-independent, applicable to landed, orbital, and even Earth-based planetary measurements, with each platform offering unique benefits and costs. Microwave observations are “diffraction limited”, meaning that for a single dish observation, the angular resolution, ϕ , (spatial resolution x) for wavelength, λ , and dish collecting diameter D is defined as: $\phi \approx 1.22 \lambda/D$, or $x \approx \text{distance} \times \tan(1.22 \lambda/D)$. Therefore spatial resolution is both wavelength, receiver, and distance dependent. Landed instruments provide high resolution data of a single location, but lack global context and may be affected by the spacecraft itself. Orbital instruments can provide global information, but at the cost of resolution. For many solar system bodies (namely Mercury, Venus, Mars, and the Moon), moderate spatial resolution mapping from large Earth-based radio observatories is also feasible.

Relevance to community 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) - all listed as primary goals in the Visions and Voyages decadal survey for terrestrial planets. While these measurements are most applicable in the short run to the Moon, they are equally suited for any terrestrial body, especially Mars and Mercury, but also to any solid body from icy moons, asteroids, to comets.

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 1c, we plot the resulting microwave brightness temperatures for the weighting functions in Fig 1b 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.

Figure 3. Global brightness temperature amplitudes at all Chang'E-2 frequencies after a time of day correction and latitudinal normalization plotted at $1/4$ degree resolution.

Figure 3 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). 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-TiO₂ 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, and ultraviolet through infrared spectral measurements of composition).

Lower frequency data can also reveal information that is completely hidden from other measurement techniques, such as buried rock or geothermal heat flux. **Figure 4** shows an example model for the Martian subsurface (with frequency range similar to that of the Mars 2020 RIMFAX GPR). Here we illustrate how microwave brightness temperature as a function of frequency would vary with depth of a 3000 kg/m³ bedrock layer covered by typical Martian regolith (thermal inertia of 150 TIU) at the Mars equator. For these models, we have a density-dependent loss tangent of ~ 0.02 for regolith and higher loss tangent of ~ 0.1 for rock (based on Feng et al., 2019), consistent with models for Martian materials (Hergert et al., 2017) in this frequency range. The rock-free line increases in brightness temperature with depth. This is due to the fact that lower-frequencies are seeing a larger volume of warm material, combined with the fact that the geothermal heat is increasing the physical temperature of the material as a function of depth. As the high-density, high-loss rock layer approaches the surface, the frequency vs brightness temperature inverts from that of rock free regolith. This is because lower frequencies are no longer sensing heat from depth, as the high-loss material prevents the energy from reaching the surface. In other words, the weighting function is essentially truncated at the depth of the high-loss rock layer.

This is not to say that it is impossible to constrain geothermal heat flux in the presence of a bedrock layer. **Figure 5** illustrates results from the same model in **Fig. 4**, but now with three different geothermal heat fluxes. Solid lines are for the model with no rock, dashed lines for a bedrock layer at 5m depth. Here we again see that despite the inversion of brightness temperature with frequency there is still a measureable difference between different heat fluxes. As material loss tangent decrease, the difference between heat fluxes becomes more prominent. Low loss

Figure 4: Model Martian microwave brightness temperatures vs. frequency for a number of assumed rock depths. Regolith “low conductivity” properties (~ 150 TIU) are from Siegler et al., 2017; rock is assumed density 3000 kg/m³ and thermal conductivity of 2.0 W/m/K. Geothermal heat flux is 20 mW/m².

Figure 5: Model Martian microwave brightness temperatures vs. frequency for rock free (solid lines) and rock at 5m depth (dashed lines) for a range of geothermal heat fluxes. Properties same as Fig. 4.

materials, like lunar highlands regolith or the Martian ice caps, could be promising locations to constrain geothermal heat flux.

Earth-Based Science

Earth-based microwave radiometry is a mature field, with measurements dating back to Peddington and Minnett (1949). Past interest and investigation of lunar microwave brightness was primarily motivated by use of the Moon as a calibration source for galactic radio telescope measurements (e.g. Linsky 1973). Such measurements generally observe the Moon as a full disc (though some short wavelengths have been spatially mapped (e.g. 3.55 cm at ~200 km resolution, Keihm and Gary, 1979) and variations at 49.3cm (Schloerb et al., 1976). With Apollo, some efforts were made to compile existing lunar full-disc radio telescope measurements (e.g. Hagfors, 1970; Muhleman, 1972; Keihm and Langseth, 1973). Keihm and Langseth (1973) used this data to derive a best-fit heat flux for the Moon. At longer wavelengths, there is a large “roll-off” where brightness temperatures become cooler. This is likely due to loss of microwave emission as the regolith becomes more dominated by rocks, adsorption of radiation in overlying layers, and the presence of a denser bedrock layer at depth.

Modern measurements have been made in association with the Chang’E radiometer calibration (e.g. Zhang et al, 2012) and new measurements are underway with the VLA (424 MHz, 1.4 GHz at ~100km spatial resolution), Arecibo (6GHz, at ~100km spatial resolution), and Greenbank (90GHz, at ~20km spatial resolution, **Figure 6**) observatories by co-authors of this white paper. Large arrays also make observations of bodies other than the Moon feasible—measurements have been made for Mercury at several 100 km resolution (Mitchell and DePater, 1994) and could be made for Mars or Venus at ~300-400 km spatial resolution using the VLA in a wider dish spacing than is available for the Moon. Further measurements with Arecibo, Goldstone, the VLA and new observatories (e.g. ALMA could greatly expand our characterization of the terrestrial planets. These goals are complimentary to those in several companion White papers on Earth-based radar measurements (Rivera-Valentín et al., 2020; Taylor et al., 2020; Virkki et al., 2020)

Orbital Science

Orbital microwave radiometer measurements have been studied (e.g. Keihm, 1984), but not flown until the 2010 Chang’E-1 and 2012 Chang’E-2 missions. Chang’E MRM data (**Figures 1, 2, 7**) give a clear picture of the science that could be done with an orbiting microwave radiometer instrument. As shown in **Figure 1 and 2**, microwave brightness temperature and diurnal amplitudes can both reveal information about the loss tangent, allowing one to map multi-scale rock and mineralogy distribution. This science is best accommodated with a new low altitude

Figure 6: Overlay of contours from the Chang’E-2 37 GHz brightness temperature maps (Fig. 1b) and our preliminary MUSTANG2 (waning-gibbous phase) filtered residual brightness temperature.

polar orbiter (Glotch et al., 2020 White Paper), allowing for a global map at multiple local times and a good characterization of diurnal brightness temperature amplitudes.

Both high and low frequency instruments would bring new discoveries. Again, as microwave observations are diffraction limited, higher frequency data has the advantage that it can be higher resolution for the same orbital altitude and antenna size. A higher-frequency instrument than the Chang'E MRMs would provide detailed structure of the near surface regolith density (aiding in identifying fresh craters and regolith overturn), small rock distribution (characterizing distal ejecta), surface composition (e.g. ilmenite content), PSR surface temperature (microwave is more sensitive than IR at low temperatures), and potentially identifying surface water frost in polar environments.

A lower frequency instrument (~300MHz -1 GHz) would excel in identifying buried rock,

characterizing global regolith depth, global bulk density (which tell us about the evolution of lunar regolith through impact bombardment), potentially mapping subsurface water ice (for resource use and studying solar system volatile delivery), and constraining global geothermal heat flux (which is critical for understanding the thermal evolution and composition of the Moon). Some of these features are apparent in the Chang'E 2 dataset as shown in **Figure 7**, which is a map midnight local time of 3GHz brightness temperature after normalization by both latitude and albedo. Here we see that areas with near surface rock (e.g. Orientale also seen in radar, Cahill *et al.*, 2014) or high TiO₂ concentrations (e.g. Mare Tranquillitatis, Sato et al., 2017) are cooler than expected at night, due to their high-loss. Areas surrounding the Procellarum basin are found to have higher than expected midnight brightness temperatures. This warm region, elevated by ~2-3 K from the background average is curiously coincident with the region of high thorium detected by the Lunar Prospector GRS instrument (e.g. Lawrence et al., 2002), and likely due to enhanced geothermal heat flow. While these data are likely to be ~10km spatial resolution, they provide a unique characterization unobtainable by other instruments.

Figure 7: CE-2 MRM 3-GHz midnight data corrected for latitude, slope, and albedo. Note the prominent cooling from high-Ti mare and rocks but residual warming of low-Ti, high Th areas in Procellarum.

Landed Science

A landed passive microwave instrument has yet to be flown to any terrestrial body. It could provide a ground truth for orbital data and a unique subsurface characterization of a landing site. In conjunction with an active ground penetrating radar (GPR), a passive radiometer would provide a powerful extra constraint on regolith thickness, density, dielectric properties and rock distribution. A landed instrument has the key advantage of spatial resolution, providing an instrument footprint with a known rock distribution or contribution, rather than averaging over a large spatial footprint from orbit or Earth-based telescope. Given the proper frequency range (~300 MHz to 3 GHz), a landed radiometer or spectrometer should also be able to provide a local

constraint on geothermal heat flux and could be an option for characterizing geothermal heat flux without requiring a deep drill. In a near polar landing site, it could identify buried ice, which will affect both thermal and dielectric properties. A rover-based landed instrument could provide a detailed and much faster transect of potential subsurface if and along-traverse heat flux.

Conclusions and Recommendations

Passive microwave instrumentation is long overdue and will provide a new look at many planetary surfaces. Technologies (which are the same as those developed for radar, earth-based weather satellites and telecom) are mature and the scientific rationale is strong. Earth's relatively transparent atmosphere in the microwave spectrum provides a unique ability to test many concepts and instruments from the ground. These instruments are readily available for flight and would provide new insights on both orbital and landed platforms. The existing data, such as ground based Arecibo and Chang'E orbital data, show that 1) Calibration is key and can be improved in future instruments, 2) a wider range of wavelengths, potentially with continuous spectral coverage, would improve science return, and 3) even a relatively low (10's of km) resolution orbital (and ground based) data set can provide a tremendous advance in science, while a landed instrument could provide ground truth for both methods.

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