SYSTEMATIC BROADBAND COMPLEX PERMITTIVITY MEASUREMENTS OF ILMENITE-BEARING LUNAR ANALOG MATERIALS. A. L. Boivin[1], D. C. Hickson[2], C. Tsai[3], R. R. Ghent[1,4], M. G. Daly[2], [1]Solar System Exploration Group, Department of Earth Sciences, University of Toronto, 22 Russell St., Toronto, ON, M5S 3B1, Canada, alex.boivin@utoronto.ca, [2]Centre for Research in Earth and Space Science, York University, Toronto, ON, Canada, [3]Department of Physics, University of Toronto, Toronto, ON, Canada, [4]Planetary Science Institute, Tucson, AZ, USA.

Introduction: Radar has long been used as a tool for remote sensing of the Moon. Earth-based, orbital, and ground radar systems in addition to microwave radiometers have all been used or are being used on the Moon to study its subsurface structure and composition. Despite an abundance of data, the lack of information on the complex relative permittivity ($\varepsilon_r^* = \varepsilon_r' - i\varepsilon_r''$) of the surface and near-surface materials hinders detailed quantitative analysis of lunar radar data. Such analysis includes determining the precise depth of radar-detected subsurface features as well as refining estimates of the abundance of subsurface materials such as the mineral ilmenite, which is known to attenuate radar and microwave signals (e.g. [1]–[3]). Significant work has made use of the fact that ilmenite attenuates radar signals to conduct geologic studies of, for instance, lava flow emplacement dynamics and regolith thickness variations in the lunar maria (e.g [4]). Microwave radiometer data are also used in brightness temperature models which require accurate measurements of loss tangents (e.g. [5]), where the loss tangent is $\tan\delta = \varepsilon_r''/\varepsilon_r'$. In order to quantitatively interpret radar and microwave data it is necessary to know how ilmenite affects loss tangent as a function of frequency and abundance. Although laboratory measurements have been made in the past in order to quantify the permittivity of lunar materials, these measurements provide a limited view of the parameter space of influence on the permittivity.

We fill this gap by presenting systematic measurements of the complex relative permittivity of powdered bytownite (a Ca-rich plagioclase feldspar) mixed with increasing amounts of ilmenite. Our measurements are made in vacuum across a broad range of frequencies (430 MHz – 8.5 GHz) and normalized to a bulk density of 1.7 g/cm^3. These systematic measurements of lunar analog materials provide new insight into the frequency-dependent effects of ilmenite content in a low-loss anorthositic matrix (analog for lunar highland rocks).

Previous Work: An extensive body of work exists on measurements of the permittivity of terrestrial and lunar samples. After analyzing 80 terrestrial rock samples it was concluded that bulk density accounts for ~50% of the variance in ε_r' and that the next most important factor is chemical composition [6]. Measurements of rock powders indicate much less variability in ε_r' [7].

Apollo lunar samples have also been extensively measured under various conditions. A review of ninety-two measurements generated a best fit of $\varepsilon' = (1.93 \pm 0.17)\rho_b$ where ρ_b is the bulk density [8]. Similar regressions were then done on both ε_r' and $\tan\delta$ using an updated dataset and it was found (for the whole dataset) that $\varepsilon_r' = 1.919\rho_b$ and $\log10(\tan\delta) = (0.038 \times (\%FeO + \%TiO_2) + 0.312 \times \rho_b - 3.260)$ fit the data, although with significant scatter for $\tan\delta$ [9]. To investigate the effects of mineralogy, available permittivity data measured at 450 MHz were re-fit to functions that depend on physical and compositional variables while holding bulk density or porosity fixed [3]. They concluded that when the data are normalized to a constant bulk density ($\rho_b = 1.7$ g/cm^3), ε_r' is constant across all samples, whereas $\tan\delta$ depends primarily on $\%TiO_2$. Since ilmenite is the primary source of TiO_2 on the Moon, a systematic study of the effects of ilmenite on the permittivity of lunar relevant materials is necessary for improved quantitative study of current or future lunar radio and microwave data.

Materials: In this work, we used bytownite sourced from the teaching collection of the Earth Sciences Department at the University of Toronto (unknown origin) and analyzed it using X-ray fluorescence (XRF). Ilmenite nodules from South African kimberlites were provided by Dr. Dan Schulze (University of Toronto, Mississauga) and analyzed using Electron Probe X-Ray Microanalysis (EPMS). Similarly to lunar ilmenite [10], our ilmenite sample contains some Mg replacing Fe (~8-10 wt%). Both samples were crushed and sieved to between 53 – 106 μm. Magnetic crusts on the ilmenite nodules were removed using magnetic separation.

Methods: We made measurements of ilmenite in a General Radio GR900-LZ6 6 cm length coaxial transmission line and measurements of bytownite and bytownite-ilmenite mixtures in a GR900-LZ15 15 cm length line connected to an Agilent E5071C ENA vector network analyzer according to the methods described in [11]. In order to remove moisture, we baked samples at 250°C for 48 hours prior to measurement and made measurements in vacuum. We processed measurement data using free and open-source software written in Python specifically for these measurements [12]. The software uses the algorithm described in [13].

Results: We present measurements of ilmenite, bytownite, and a bytownite-ilmenite mixture with 10 wt % ilmenite normalized to a bulk density of 1.7 g/cm^3. Figure 1 shows the real part (ε_r') of the complex relative permittivity and the loss tangent (tan δ) of ilmenite. From 800 MHz to 8.5 GHz the values range from 8.2 to 5.4 for ε_r' and 0.22 to 0.29 for tan δ. Both the real part and tan δ clearly show frequency dispersion in this frequency range. Figure 2 shows the real part of the relative permittivity of bytownite and the 10 wt% ilmenite in bytownite mixture along with the density-dependent relationship derived from lunar data by [9] and the corresponding loss tangents. The addition of 10 wt% ilmenite to bytownite increases the real part of the permittivity as well as the loss tangent (and therefore the attenuation) and also introduces frequency dispersion to both. The loss tangent regressions performed by [9] (dependent on the bulk density and FeO + TiO_2 and derived from 450 MHz lunar data) and by [3] (dependent on TiO_2 only and derived from 450 MHz lunar data normalized to 1.7 g/cm^3) are also plotted. Both regressions are plotted for 10 wt% ilmenite and ρ_b = 1.7 g/cm^3. Although the relationship derived by [3] accurately predicts the lower-frequency results for the bytownite-ilmenite mixture (note however high uncertainty at that frequency), our results here show that it is not valid at higher frequencies due to the introduction of frequency dispersion effects by ilmenite.

Work currently being done to expand these results includes the measurement of mixtures ranging from 1 wt% to 20 wt% ilmenite in bytownite as well as Cole-Cole modeling ([14]) of the results to elucidate the relevant relaxation mechanisms causing the frequency dispersion.

References: [1] Campbell B. A. et al. (1997) *JGR*, vol. 102, no. E8, pp. 19307–19320. [2] Ghent R. R. et al. (2005) *JGRP*, vol. 110, no. 2, pp. 1–19. [3] Fa W. and Wieczorek M. A. (2012) *Icarus*, vol. 218, no. 2, pp. 771–787. [4] Morgan G. A. et al. (2016) *JGRP*, vol. 121, no. 8, pp. 1498–151. [5] Siegler M. et al. (2018) *Deep Space Gateway Science Workshop,* abstract #3123. [6] Ulaby F. T. et al. (1988) Rad. Lab. Tech. Rep. No. 023817-1-T. Dept. of Elect. Eng. and Computer Sci., Univ. of Michigan. [7] Campbell M. J. and Ulrichs J. (1969) *JGR*, vol. 74, no. 25. [8] Olhoeft G. R. and Strangway D. W. (1975) *Earth Planet. Sci. Lett.*, vol. 24, no. 3, pp. 394–404. [9] Carrier III W. D. et al. (1991) in *L. Sourcebook*, Cambridge University Press, pp. 522–530. [10] Papike J. et al. (1991) in *L. Sourcebook*, Cambridge University Press, pp. 121–181. [11] Boivin A. L. et al. (2018) *JGRP*. [12] Boivin A. L. and Hickson D. (2018) "permittivitycalc (Version v0.5.0)." Zenodo, DOI: 10.5281/zenodo.1469776. [13] Boughriet A. H. et al. (1997) *IEEE Trans. Microw. Theory Tech.*, vol. 45, no. 1, pp. 52–57. [14] Cole K. S. and Cole R. H. (1941) *J. Chem. Phys.*, vol. 9, no. 4, pp. 341–351.

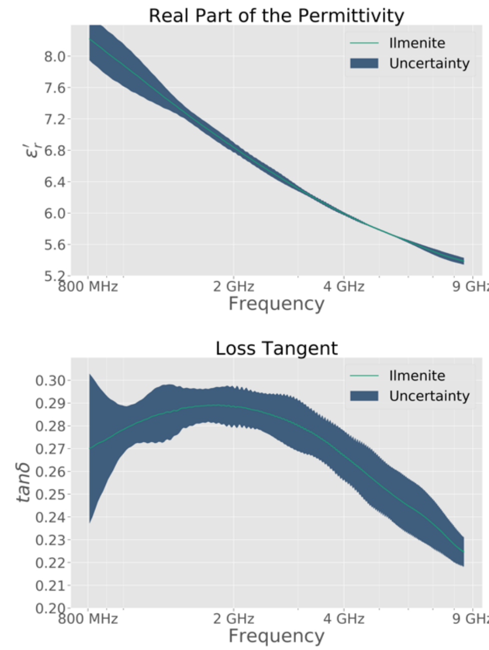

Figure 1: Real part of the permittivity and loss tangent of powdered baked ilmenite from 800 MHz – 8.5 GHz. Normalized to 1.7 g/cm^3.

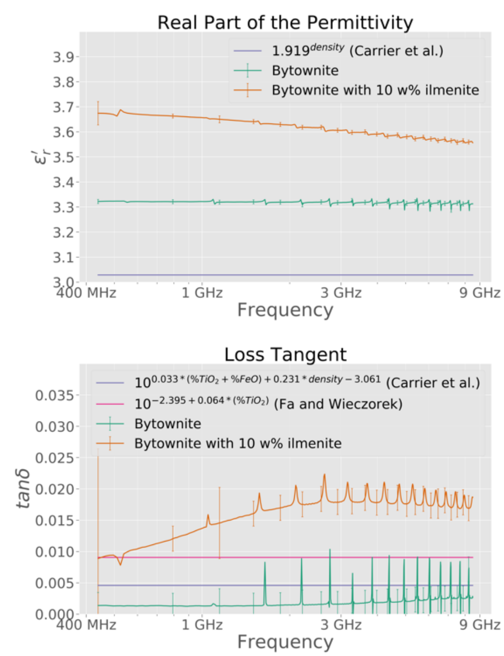

Figure 2: Real part of the permittivity and loss tangent of powdered baked bytownite and bytownite-ilmenite mixture from 430 MHz – 8.5 GHz. Normalized to 1.7 g/cm^3. Spikes in data are due to a well-documented resonance effect (see e.g. [11], [13] and references therein).