MICROWAVE PERMITTIVITY AND PERMEABILITY MEASUREMENTS ON LUNAR SOILS. Martin Barmatz[1], David Steinfeld[1], Shelley B. Begley[2], Daniel Winterhalter[1], and Carlton Allen[3], [1]Jet Propulsion Laboratory, California Institute of Technology, M/S 79-24, 4800 Oak Grove Drive, Pasadena, CA 91109, E-mail: Martin.B.Barmatz@jpl.nasa.gov, [2]Agilent Technologies, Inc., Santa Rosa, CA 95403, [3]NASA Johnson Space Center, Houston, TX 77058.

Introduction: There has been interest in finding ways to process the lunar regolith since the early analyses of lunar samples returned from the Apollo moon missions. This fact has led to proposals for using microwaves to perform in-situ processing of the lunar soil to support future colonization of the moon [1]. More recently, there has been speculation that the excellent microwave absorption of lunar soil came from the nanophase iron content in the regolith [2]. The motivation for the present study was to begin obtaining a more fundamental understanding of the dielectric and magnetic properties of the regolith at microwave frequencies. A major objective of this study was to obtain information that would help answer the question about whether nanophase iron plays a major role in heating lunar soils. These new measurements over a wide frequency range can also determine the magnitude of the dielectric and magnetic absorption and if there are any resonant features that could be used to enhance processing of the regolith in the future. In addition, these microwave measurements would be useful in confirming that new simulants being developed, particularly those containing nanophase iron, would have the correct composition to simulate the lunar regolith. The results of this study suggest that nanophase iron does not play a major role in heating lunar regolith.

Microwave Measurements: Microwave permittivity and permeability measurements were performed on four lunar soil samples at the Johnson Space Center (JSC) Lunar Experiment Laboratory. Samples from the dark mare areas and bright highland regions of the moon were studied. These are the first direct measurements of the microwave permeability of lunar soil at microwave frequencies. Information regarding the samples studied at JSC is given in Table I. The surface

Table I. Information on JSC lunar soil samples.

Sample #	Apollo Flight #	Type of Soil	Sample Designation
1	17	Mare (Submature)	75081,14
2	16	Highland (Mature)	64501,12
3	11	Mare (Mature)	10084,27
4	14	Highland (Submature)	14163,179

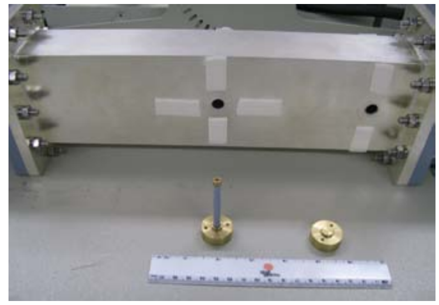

Fig. 1. Rectangular cavity for near 2.45 GHz measurements

exposure maturity was determined from maturity index ratio I_s/FeO [3]. Two experimental techniques were used. A rectangular microwave cavity was specially designed to operate in a TE_{10n} mode near 2.45 GHz. Samples were contained in a small diameter, thin walled, cylindrical Teflon tube that could be inserted into a hole in the center or near the end of the cavity as shown in Fig. 1. Even-valued "n" index modes corresponded to having a maximum *H*-field, zero-*E* field condition, while odd-valued "n" index modes corresponded to having a maximum *E*-field, zero-*H* field condition for the sample in the center hole. The hole near the cavity end was used to determine the permittivity for the TE_{104} mode. The permittivity and permeability were determined using a cavity perturbation approach from measurements of the shift in the cavity resonant frequency and quality factor with and without the sample inserted [4]. Measurements were also obtained over the frequency range 8.2 - 40 GHz using a waveguide technique. For the waveguide studies, the permittivity and permeability were obtained from measurements of the reflection and transmission coefficients of a material sample placed in a waveguide [5]. All measurements were performed using an Agilent E8364B Network Analyzer.

Figure 2 shows the imaginary relative permittivity obtained from the low frequency cavity. The size of the symbols represents the uncertainty in the measurements. It is seen, as expected, that the Mare samples (#1 and #3) that contain large amounts of FeO and TiO_2 have a large ε_r'' while the Highland samples (#2 and #4) with low FeO and TiO_2 content have smaller ε_r'' values. Figure 3 shows the imaginary relative permeability obtained from the cavity. Again the size of

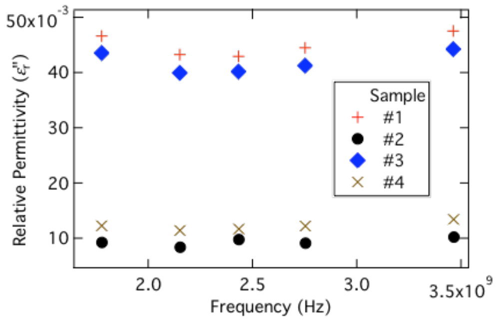

Fig.2. Imaginary relative permittivity vs frequency

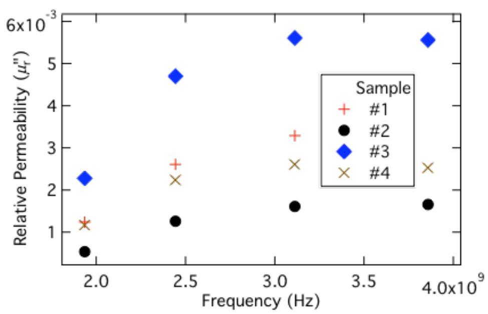

Fig. 3. Imaginary relative permeability vs frequency

the symbols represents the uncertainty in the measurements. Here there is no clear correlation except that μ_r'' increases with frequency possibly reaching a maximum near 3.5 GHz. What is important to note is that dielectric contribution to absorption ε_r'' is over 10 times larger that the magnetic contribution μ_r''.

Conclusions: The absorption of microwaves depends on the magnitude of the imaginary parts of the permittivity, ε_r'', and permeability, μ_r''. The time-averaged power dissipated, *P*, in a volume *V* due to dielectric and magnetic losses is given by

$$P = (\omega/2)\int_V \left(\varepsilon_0 \varepsilon_r'' |E|^2 + \mu_0 \mu_r'' |H|^2\right) dv \ ,$$

where ε_0 is the permittivity of free space, μ_0 is the permeability of free space, *E* is the electric field strength and *H* is the magnetic field strength. This expression is valid so long as there is a linear relationship between the *D* and *E* fields and the *B* and *H* fields. It is seen that the power absorbed depends on the applied electric and magnetic fields as well as the value of the imaginary components. So, where a sample is situated in a microwave environment can strongly influence the resultant absorption. We have calculated the absorption for the TE_{104} cylindrical cavity mode at a frequency of 2.45 GHz for positioning lunar Highland sample #4 at positions of maximum *E* and *H* fields in our cavity. For this case, we found that the dielectric contribution was 4 times greater than the magnetic contribution.

From our measurements, we conclude that the magnetic components of the lunar regolith (including nanophase iron) are not the dominant contribution to microwave absorption at a frequency of 2.45 GHz at room temperature. This same conclusion can be drawn from our other higher frequency measurements. There certainly is the possibility that at higher temperatures the imaginary relative permeability could significantly increase relative to the imaginary relative permittivity. Future temperature dependent measurements are required to clarify this assumption.

The contribution of nanophase iron to microwave absorption has been studied using ferromagnetic resonance (FMR) techniques [6]. Those measurements at 9.5 GHz show a significant absorption peak at high dc magnetic fields around 3.5×10^3 Oe. The interpretation of those measurements suggests that nanophase iron should not contribute to absorption under low magnetic field conditions, where only other larger grain size magnetic components of the lunar regolith will dominate the absorption. The magnetic field range around the FMR over which the nanophase iron contributes could be reached if kilo-Oersted magnetic fields could be generated within a microwave processing applicator. However, a more realistic situation for microwave processing of the lunar regolith would require placing larger samples within the applicator. Then, the average ac magnetic field within the larger sample would be much smaller than the FMR peak value. It appears that using the FMR to heat the lunar regolith may not be feasible.

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