Analysis of the Complex Permittivity and Permeability of a Martian Soil Simulant from 10 MHz to 1 GHz

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ABSTRACT – This paper presents the results from an analysis of a Martian soil simulant over the frequency range of 10 MHz to 1 GHz. The motivation is to provide an estimate of the electrical properties, complex permittivity and permeability, of a soil that can be expected on the surface of Mars. The test procedure involves measuring the reflection and transmission properties of the soil using a slotted section of coaxial transmission line. With the soil acting as the dielectric of the coaxial transmission line, four sets of measurements were collected using a network analyzer. These measurements include transmission through the soil and three sets of reflection measurements with the attached loads: short, open, and 50 Ohms. Next, these measurements are compared to analytic values; these are calculated by representing the coaxial transmission line by a signal flow graph and assuming initial values of the permittivity and permeability. An iterative approach is then used to minimize the root-mean-square error and determine approximate values of the permittivity and permeability. Finally, the results are presented over the frequency range of interest.

INTRODUCTION

This paper presents the results from an analysis of a sample of Martian soil simulant, JSC MARS-1, obtained from the Johnson Space Center in Houston, Texas. The simulant is claimed to approximate the reflectance spectrum, mineralogy, chemical composition, grain size, density, porosity, and magnetic properties of the oxidized soil on Mars [1]. The results of the analysis intend to give an estimate of the constitutive parameters, complex permittivity and permeability, of the soil. These values will provide useful information concerning the performance of a ground-penetrating radar (GPR) on Mars. The test procedure involves measuring the reflection and transmission properties of the soil using a coaxial transmission line [2,3]. From these measurements, the permittivity and permeability can be estimated using a least-square-error approach.

MEASUREMENT

As shown in Fig. 1a, measurements of the soil were collected using a network analyzer connected to an air-dielectric slotted section of coaxial transmission line. The operating frequency ranges from 10 MHz to 1 GHz. The air-dielectric slotted line, shown in Fig. 1b, is used because it can be easily filled with the soil allowing measurements of the transmission and reflection properties. The measurement procedure is as follows. First, the network analyzer is calibrated at the terminals of the coaxial line. Next, the S-parameters, transmission and reflection coefficients, of the slotted transmission line without the soil present are measured for a calibration standard. The slotted section is then filled with the soil simulant and four sets of measurements are made. These measurements include transmission through the soil and three sets of reflections with the loads: short, open, and 50 Ohms.

ANALYSIS

The least-square-error approach involves comparing the measured results to a set of analytical results that are obtained by calculating the S-parameters using estimated values of the permittivity and permeability. These estimated values are slightly changed and the error is recalculated. If the error decreases, the values are changed in the same direction, and, alternatively, if the error increases, the values are changed in the opposite direction. This procedure is iterated until only a slight amount of error improvement is attained with each iteration.

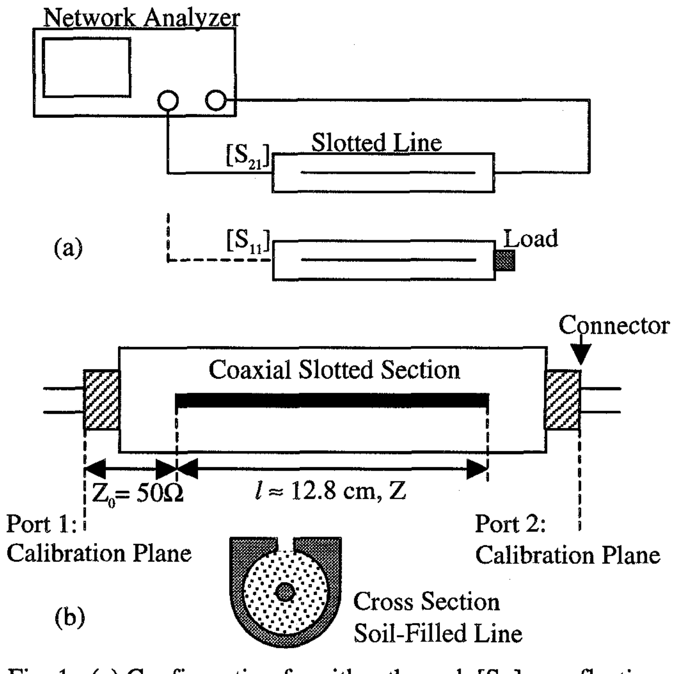

Fig. 1. (a) Configuration for either through $[S_{21}]$ or reflection, $[S_{11}]$ measurements. (b) Coaxial slotted section of transmission line with cross-sectional view.

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Signal Flow Graph

A signal flow graph was constructed to determine the analytical values of the transmission [S_{21}] and reflection [S_{11}] coefficients of the transmission-line fixture. With respect to Fig. 2, the value, A, accounts for the short length of transmission line, Z_0, between the calibration planes of the network analyzer and the edge of the slotted line. The characteristic impedances are expressed as

$$Z_0 = 50\Omega \text{ and} \tag{1}$$

$$Z = \sqrt{\frac{\mu_r}{\varepsilon_r}} Z_0 , \tag{2}$$

where ε_r and μ_r are the complex permittivity and permeability of the soil simulant, respectively. The reflection coefficient at the soil interface is expressed by

$$\Gamma = \frac{Z - Z_0}{Z + Z_0} = \frac{\sqrt{\mu_r} - \sqrt{\varepsilon_r}}{\sqrt{\mu_r} + \sqrt{\varepsilon_r}} , \tag{3}$$

while the transmission coefficients are determined by the relations

$$T_{IN} = 1 + \Gamma \text{ and} \tag{4}$$

$$T_{OUT} = 1 - \Gamma . \tag{5}$$

Finally, the propagation, β, and attenuation, α, constants within the slotted line are expressed by

$$\alpha + j\beta = j\frac{\omega}{c}\sqrt{\mu_r \varepsilon_r} . \tag{6}$$

Air-Filled Line (Calibration)

The transmission coefficient of the coaxial line was originally measured with an air dielectric to calibrate for the constant, A, appearing in the signal flow graph. In this configuration, the characteristic impedance of the slotted section becomes 50Ω, all reflection coefficients are zero, and all transmission coefficients are unity. Using the relationship

$$S_{21} = A^2 \exp\{-j\beta_0 l\}, \tag{7}$$

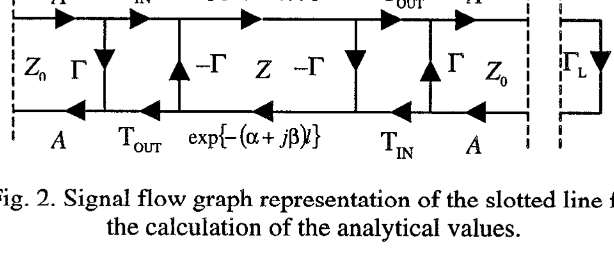

Fig. 2. Signal flow graph representation of the slotted line for the calculation of the analytical values.

the value of A is determined from

$$A^2 = S_{21} \exp\{j\beta_0 l\}, \tag{8}$$

where β_0 is the propagation constant in free space and l is 12.8 cm.

Soil-Filled Line

Four sets of measurements were collected after the slotted lined was filled with the soil dielectric. These measurements include:

(i) Through Transmission ($\Gamma_L = 0$)
(ii) Matched Load ($\Gamma_L = 0$)
(iii) Open Load ($\Gamma_L = 1$)
(iv) Short Load ($\Gamma_L = -1$)

The transmission, S_{21}, or reflection, S_{11}, coefficient for each configuration is calculated analytically by applying Mason's Rules [4] to the signal flow graph with the appropriate reflection coefficient. The error is determined by comparing the measured values with the calculated values

SOIL MODEL

A simple Debye-Pellat relaxation equation was used as a model for the frequency dependency of the permittivity and permeability of the soil simulant. These models are expressed for the complex permittivity and permeability as

$$\varepsilon' - j\varepsilon'' = \varepsilon_\infty + \frac{\varepsilon_s - \varepsilon_\infty}{1 + j\omega\tau_\varepsilon} \text{ and} \tag{9}$$

$$\mu' - j\mu'' = \mu_\infty + \frac{\mu_s - \mu_\infty}{1 + j\omega\tau_\mu} . \tag{10}$$

During each iteration, a single parameter of these expressions is slightly changed. If the resulting error decreases, the deviation was in the correct direction and the process is iterated. If the resulting error increases, the deviation was in the wrong direction, and an opposite direction is chosen. This procedure is iterated until the decrease of error for each iteration is negligible.

RESULTS

Table 1 shows each parameter and the value after the final iteration. Fig. 3 shows a comparison of the measured and calculated coefficients using the soil models described above, and Fig. 4 shows the relative permittivity and permeability as functions of frequency. These results show a significant amount of loss appearing in the imaginary component of the permittivity. This loss is most likely associated with the high iron content of the soil. The relative permeability does not seem to indicate any significant magnetic properties of the soil.

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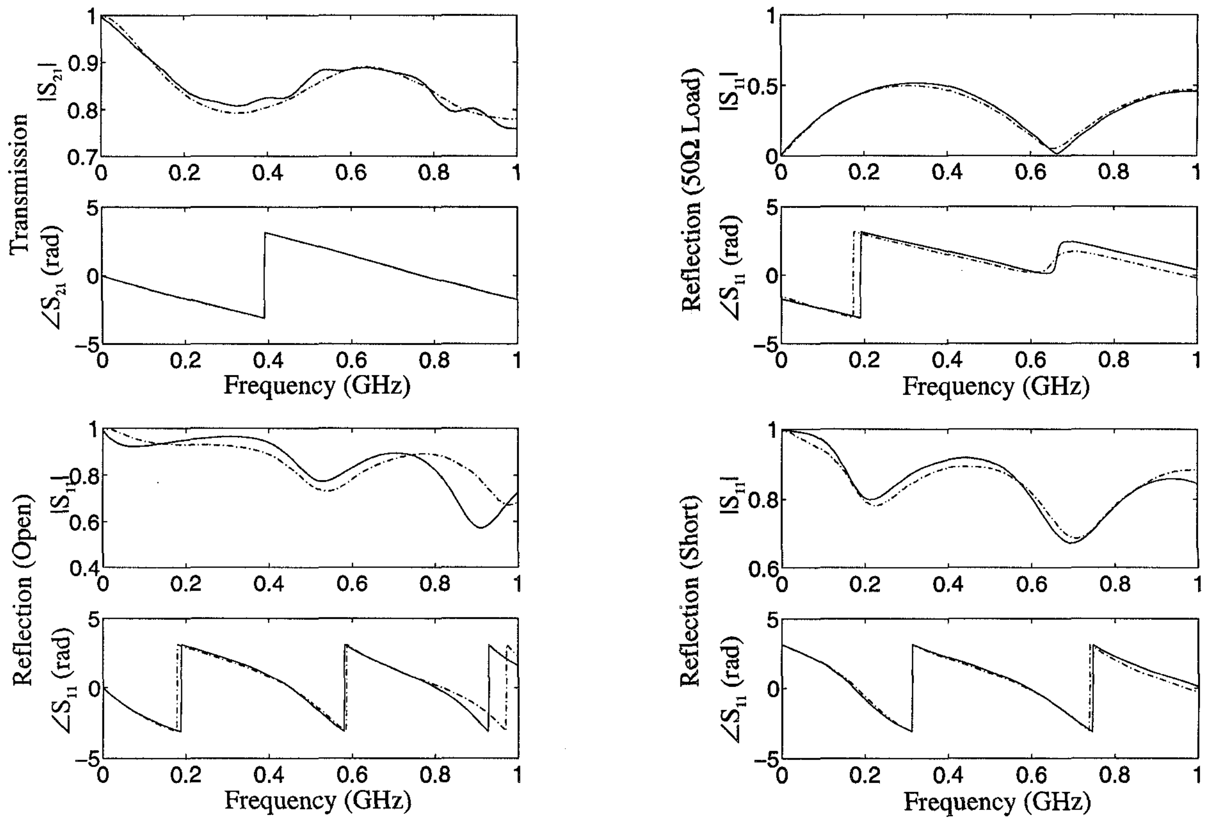

Fig. 3. Comparison of the measured (solid lines) and calculated (dashed lines) S-parameters using the soil model in Table 1.

Table 1. Soil parameters and least error values.

Parameter		Value
ε_∞	Permittivity at Infinity	3.12
ε_s	Static Permittivity (d.c.)	3.57
τ_ε	Permittivity Relaxation Time	0.041 ns
μ_∞	Permeability at Infinity	1.01
μ_s	Static Permeability	1.2
τ_μ	Permeability Relaxation Time	0.2 ns

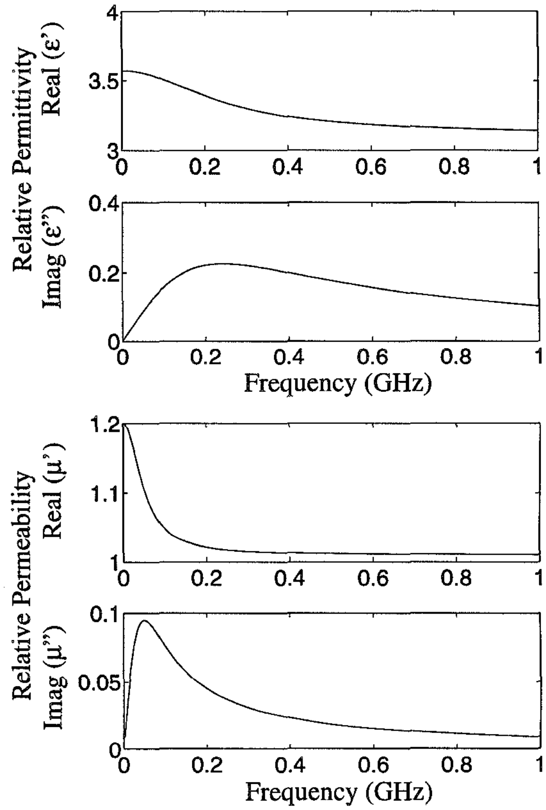

Fig. 4. Relative permittivity and permeability.

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