Multiple Interface Systems and Applications

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Abstract—Single interface reflection and refraction systems is common topic in most introductory electromagnetic theory courses. However, the notion of two, three, or even more interfaces are not as well covered unless the interfaces are in a repeating pattern. This precludes using the ideas one would learn about how EM waves interact with changing interfaces in real world applications. In order to take EM theory about how waves behave at interfaces and create useful applications, multiple interface systems must be accurately understood and modeled. Thus, this paper will describe how multiple interface systems with organic materials behave. The application used to demonstrate the importance of such systems and modeling is predicting the distance to ground water through soil, dirt, and other organic material.

Index Terms—Electromagnitism, EM Theory, Water Table, Double Interface

1 Introduction

Nearly 2 billion people actually lack access to clean water which may very well be found under the ground on which they stand [2]. The composition of sediment and the distance to a reserve of water underground will uniquely determine how a water well would be drilled and operated[1]. This information, when analyzed via hydrogeological techniques, directly affects the feasibility, environmental safety, and cost of building life-saving wells. The experiment detailed here is an attempt to model one such environment using cost-effective electromagnetic devices and techniques that would aid in conducting a water table survey.

2 Approach

The physical setup of the experiment used to extract relevant values consisted of a plastic tub approximately 1′ by 1′ by 3′ in size, various organic materials (soil, mulch, water, etc), and a wood and mesh container to suspend materials above the interface of the water.

The data analysis and model building was handled in MatLab. Initially, the approach was to compare and fit a model developed using EM theory to the data gathered, but we decided to abandon attempting to develop a model from basic EM theory due to unexpected complexity and simply fit a mathematical model to the data gathered.

2.1 Experimentation

The first step was to individually characterize generic potting soil, landscaping mulch, cinder block stone, and a soil and mulch composite. Assuming that these organic materials are highly non-magnetic, we extracted the permeability ϵ of each from the scattering parameters using the vector network analyzer as seen in Figure 1.

We then proceeded to stack the sediment on water and a cinder block base. Figure 2 and 3 illustrate our two experimental setups where the sediment is firstly suspended above the water with an air gap between the materials and secondly where the water saturates a middle layer of sediment. This was done to illustrate the contrast between ideal stacked layers and a more realistic profile of saturated and unsaturated sediment.

We then recorded the phase difference and scattering parameters as we varied the water levels in the system. A key assumption made in these measurements is that the water is the most reflective material present and that most signal reflection that can be detected occurs at the surface of the water. Additionally, the cantenna was placed directly above the sediment surface and kept still so all calculated distances can be assumed to correspond to the depth of the soil to the surface of the water.

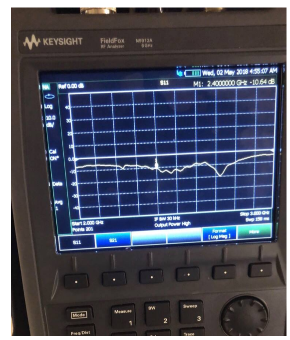

Fig. 1. VNA, vector network analyzer, showing scattering parameter

Fig. 2. Varying air gap multiple interface system

Fig. 3. Varying distance to water level single interface experimental setup

2.2 Analysis

The phase difference and scattering parameter data was imported into MatLab for analysis. A few transformations were applied to the data in order to extract more relevant metrics for the analysis. The first transformation isolates phase as a portion of the wavelength. We will refer this metric as a distance factor which is calculated as follows:

$$\text{Distance factor} = \frac{\phi}{2\pi}\lambda_0$$

Where ϕ represents the measured phase offset and $lambda_0$ represents the wavelength.

Where the scattering parameter is concerned, the most relevant metric related to it is the effective epsilon which is calculated by using the following relationship for interfaces:

$$S_{11} = \frac{\eta_2 - \eta_1}{\eta_2 + \eta_1}$$

$$\eta = \sqrt{\frac{\mu}{\epsilon}}$$

Here, S_{11} is the measured scattering parameter η represent the characteristic impedance of the medium, μ is the permeability of the medium, and η is the permittivity of the medium[3]. After applying the above transformations, each of our data points now had an effective epsilon and distance factor associated with it.

3 Results

After the data was processed, we generated plots to discover trends that would indicate how the water depth changes with respect to different distance factors and effective epsilons. A summary of the characterizing data (raw S_{11} and phase measurements) of each experimental set up are shown in Table 1. It also includes a third column for an effective relative permittivity. We took an average for this data because while there was an upward trend in the dielectric constant as the water level rises, we would expect for this value to be independent of volume. We can account for this difference however in the imperfections of using such highly lossy mediums [4].

Table 1

Material	S_{11} (dB)	Phase	ϵ_{eff}
Water	-14.03	-26.69	2.23
Stone	-12.5	-1.884	2.63
Mulch	-10.35	31.91	3.5
Mulch and Water	-11.61	9.352	3.43
Soil and Water	-7.64	16.37	3.37
Soil, Mulch and Water	-10.03	30.4	3.68

The plots, Figures 4 and 5, give a sense of the trend that exists between the metrics and the distance to the water. For example, the effective epsilon as a function of distance to the water has a clearly positive correlation, but the variation in between materials is much lower than the trend we notice in the second plot. This plot shows the negative correlation between distance factor and distance to the water, but the mixture of soil and mulch actually drags the curve away from the more uniform material curves.

4 Conclusion

When running our experiment once more to verify the accuracy of this model for the known environment, the strengths and weaknesses of using this model as a detection tool became evident. The primary drawback of using this

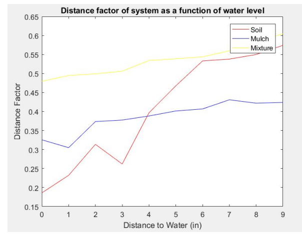

Fig. 4. Effective epsilon trends upward with distance to water level

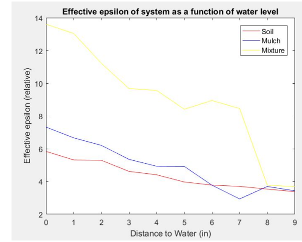

Fig. 5. Distance factor trends downward with distance to water level

model to determine depth to the surface of a water table is that any slight horizontal shift of the antenna location resulted in vastly different phase delay readings. This is due to highly non-uniform composition of the sediment.

Deeper inspection of the phase delay information from the model verification experiment showed that there was strong evidence that changes in the water table could be tracked, without calibrating a specific phase measurement to the distance to water. Testing phase at arbitrary water levels and matching the phase shift as more or less water was added indicated that 1 to 2 inches of changes in the water level could be detected within 25 % error. Thus, our model could be used to track deltas in the water level relatively well, but not provide an absolute value. Improvements in the uniformity of the material via various types of stone to mitigate phase variation would allow the model to more accurately track reality and reduce error. Additional construction of a stable mount for the antenna would also allowed for increased precision in our data collection.

Furthermore, this system would be more appropriate as a fixed tool to monitor the state of a known water table rather than to detect where such a table exists underground. In the context of hydrogeology, this information is essential to evaluating water use and the impact it has on the integrity of the ground composition. Possible future steps include designing a larger antenna that could be used for a much lower frequency signal. Monitoring the levels of a shallow water well at around 100 ft would require a wavelength at least as long as the depth to the water table. This corresponds to a $\approx$ 9.8 MHz wave. Further calculations would be necessary to fine tune an antenna of this scale as well as keep it at a reasonable, cost effective design.

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