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# A Proposal for Detection of Underground Water Contamination via Multilayer Reflection Approach

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**Abstract:** Contamination and degradation in the quality of the fresh water under the ground is one of the major problems of our world. Water quality on the other hand, determined by the physical, chemical and biological compounds in the water. TDS (Total Dissolved Solid), salinity, dissolved oxygen, temperature, metabolic wastes, toxic compounds and conductivity are some of the major indicators of the water quality. These items are sometimes correlated and any increase in one factor may decrease/increase other factors as well. The aim of this work is to develop an idea about the contamination due to chemicals dissolved or biological anomalies in the water. Mainly the indicator of this change has been examined by the change in the conductivity parameter, which is a major electrical property that affects the Electromagnetic reflectivity of the surface ground.

**Index Terms:** Multilayer Reflection, contamination, conductivity

## 1. Introduction

Underground water layer quality has crucial importance for the public health [1]. Studies has been carried on this subject, especially in biology, chemical and environmental sciences [2]. In this study, we modeled the geographic structure which is composed of water and soil, as a multilayer structure and by observing changes in the conductivity, and made a proposal for the purity level of the water. In Fig. 1, relation between the conductivity and water quality which is the major motivation of this study, is given [3].

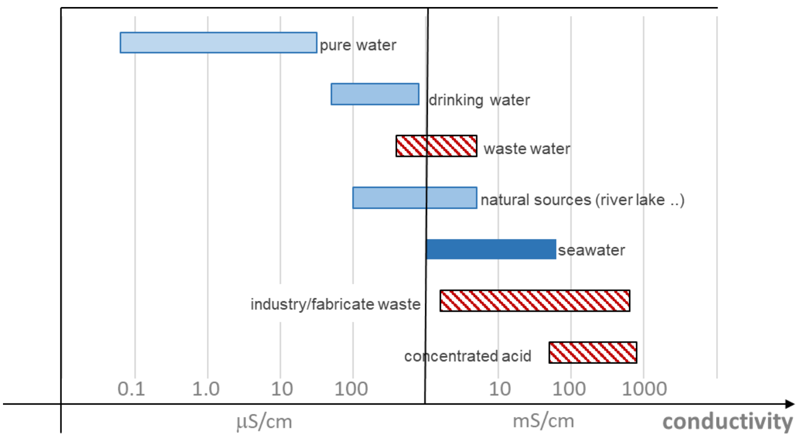


Fig. 1. Water classification vs conductivity, factors that affect water quality

There are several indicators about the water quality other than conductivity; Total Dissolved Solids (TSD), temperature, pH level, toxic compounds, dissolved oxygen (which indicates amount of organic compounds in unit volume), and salinity are some of these [4]. TSD among these, one of the most commonly used solution for this problem, which indicates parts per million (ppm) in mg per unit volume. This scale presents a range from distilled water

 

(*0*) to the maximum contamination level *(500+)*. Besides, TSD is a correlated parameter to conductivity, due to its character as a metric since the amount of dissolved solids is a major factor for determining conductivity. These two parameters are especially useful in studying seawater intrusion to the drinking water [5]. On the other hand, some organic compounds like oil and bacteria, when mixed in water, decreases conductivity of the water [6] (Fig. 1).

In this study we will focus on the measurement of conductivity indicator and propose a measurement and evaluation technique from water quality point of view. Actually, this parameter itself is not sufficient but serves as a good indicator for the presence of the pollutants[7]. Another major advantage of this method is measurement process of conductivity is achieved without any external invasive or destructive affect. Since each water source tends to have an average constant range of conductivity, clean water conductivity, once established and recorded, can be used as a reference. Later, measuring the modifications in the conductivity in different time slots, any change detection could then be an indicator that a discharge or some other source of pollution has diffused into the water resource [8].

Government bodies in US such as EPA (Environmental Protection Agency) and other groups like Safe Drinking Water Act (SDWA) take care about the water quality and public health, publishing scientific works and annual reports about source water (such as rivers, streams, lakes, reservoirs, springs, and groundwater). Groundwater, among these, is the main interest of our work, since we aim to predict ground water quality without any invasion or destructive action to the surface. In Fig. 1, drinking water quality was shown to be between $0 < \sigma < 700$ µSiemens/cm [1],[2].

Major research objective in this study is to measure this parameter of groundwater, which lies beneath Earth's surface in soil spaces and in the fractures of rock formations. Authors hope to achieve a neat and relatively easy identifier for the underground water contamination. This method is hoped to be accepted and generalized, which is needed to visualize materials beyond an invisible layer.

## 2. Methodology

As described generally in Fig. 2, incident, scattered and reflected fields are calculated for each interface postulated by Electromagnetic theory and multireflection phenomena [9],[10].

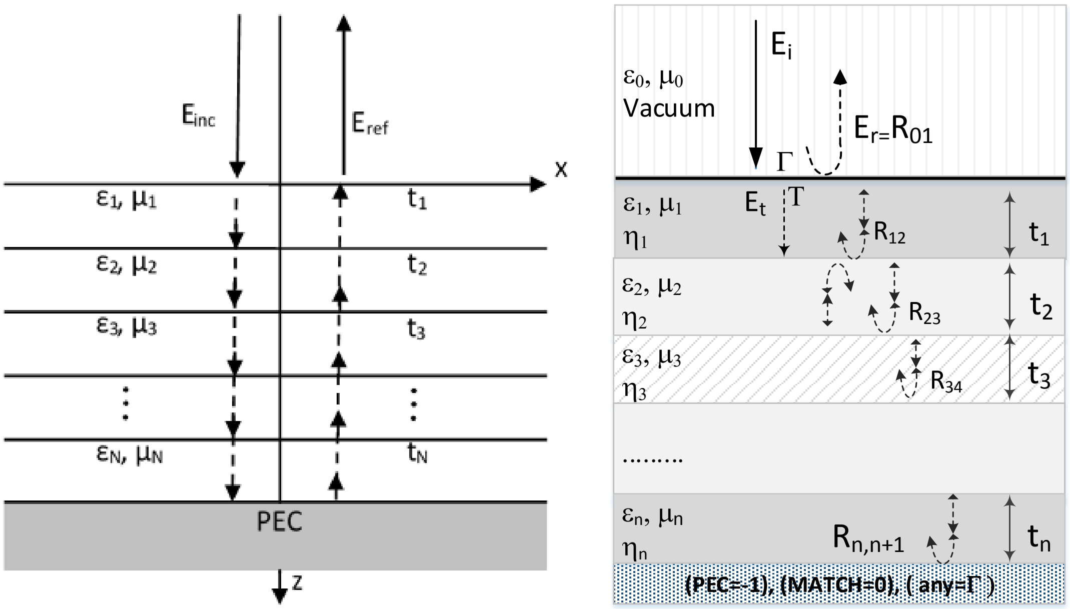


Fig. 2. General Modeling of a Multilayer Structure

In Fig. *3*, a general ground water structure presented. The term water table, which is the major layer to be investigated and parameterized, is the depth at which soil pore spaces or fractures and voids in rock become completely saturated with water [3].

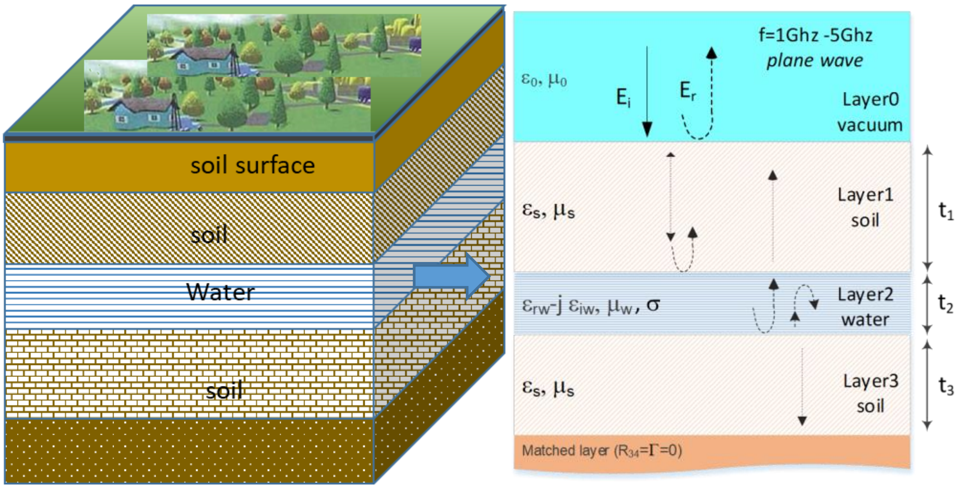


Fig. 3. Modeling of a sample earth with a ground water layer

## 3. Modeling

Groundwater layer has been modelled as in Fig. 3. Electric parameters for the water and soil structures has been given in Table 1. As a sample run, a water layer was placed in between soil (dry) layers. Soil and water types differ in nature, thus depending on the structure, their parameters shall be selected accordingly. With this respect, our modeling seems to be similar to the one presented in [10]; but it should be kept in mind that in that particular study, the authors tried to identify the water pollution inside the underground pipelines with time domain approaches. On the other hand, we are trying to examine a similar structure (but an underground water layer, not a pipe); and we are trying to perform our analyses in frequency domain.

Table 1. Material Electrical properties, used in terrain problems

| | r | i | r | i |
|---|---|---|---|---|
| **Vacuum** | 1 | 0 | 1 | 0 |
| **Soil (dry)** | 2.53 | 0.0091 | 1 | 0 |
| **Water (pure)** | 78 | 19.08 | 1 | 0 |
| **Sand (dry)** | 5 | 0.24 | 1 | 0 |
| ***User Defined*** | $\varepsilon_r$ | $\varepsilon_i$ | $\mu_r$ | $\mu_i$ |

### *3.1 Formulation*

Maxwell's Equations (Ampère's Law) [10] has been used in the study:

$$\nabla \times H = (\sigma + j\omega\varepsilon)E = \varepsilon_c E \tag{1}$$

Relation between the conductivity and complex permittivity is given by:

$$\begin{aligned} \varepsilon_i(f) &= \varepsilon_0\varepsilon_c = \varepsilon_0\left(\varepsilon_i'(f) - j\varepsilon_i''(f)\right) \\ \mu_i(f) &= \mu_0\mu_c = \mu_0\left(\mu_i'(f) - j\mu_i''(f)\right) \end{aligned} \tag{2}$$

In our study, permeability ($\mu$) was taken as constant, so this parameter is out of interest. On the other hand, imaginary part of the permittivity is responsible for conductivity, which is the primary parameter of this study:

$$\varepsilon_i' = \varepsilon_r; \quad \varepsilon_i'' = \frac{\sigma}{2\pi f} \rightarrow \sigma = 2\pi f \varepsilon_i'' \tag{3}$$

*3.2 Modeling*

Overall reflection coefficient for multilayer structures are given by recursive formula [9]. "R" represents the reflection coefficient between any two layers. Indices represents layers. Layer "0" is the top layer where the source was located, in our case, air or vacuum. $R_{0,1}$ is the resultant reflection coefficient, seen at the surface and representing all the internal reflections caused by the inner layers (Fig. 1). The general expression of reflection coefficient at the interface between layers (*i*) and (*i*+1) can be written as in Eq.s (4) and (5):

$$R_{i,i+1} = \frac{r_{i,i+1} + R_{i+1,i+2} e^{-j2k_{i+1}t_{i+1}}}{1 + r_{i,i+1} R_{i+1,i+2} e^{-j2k_{i+1}t_{i+1}}} \tag{4}$$

Where;

$$r_{i,i+1} = \frac{\mu_{i+1} k_i - \mu_i k_{i+1}}{\mu_{i+1} k_i + \mu_i k_{i+1}} \tag{5}$$

and $k_i$ is the wavenumber of $i^{th}$ layer given by;

$$k_i = 2\pi f \sqrt{\varepsilon_i \mu_i} \tag{6}$$

Depending on the structure, in order to simulate PEC (Perfect Electric conductor), $R_{N,N+1}$ is chosen to be "*-1*", and *"0*" to simulate the matched layer. The code permits any value in the range [*-1, 1*] in order to simulate any layer, too. The recursive formulation for the total reflection coefficient $R_{0,1}$ is implemented and calculated by a MATLAB script. We selected the termination as "matched" in order to simulate lower soil structure that goes down into the earth, stretching to infinity.

Reflection coefficient at the surface has been calculated by the recursive equations given in Eq.s (4), (5) and (6).

*3.3 Adding Noise*

In order to increase the simulation implementation closer to real world, we have added random noise for each frequency component. Another noise factor, which is directly proportional to reflected signal amplitude, is also added. Starting from the definition of SNR (Signal to noise ratio) concept;

Noise source1:

$$SNR = 20\log\frac{ReflectedSignal}{noise(1)} \rightarrow noise(1) = \frac{ReflectedSignal}{10^{SNR/20}} \tag{7}$$

Noise source2 (constant):

$$noise(2) \cong \%3 \times ReflectedSignal \tag{8}$$

## 4. Simulation Results

Simulations are performed mainly in two categories: Frequency Sweep for different conductivities and Conductivity sweep for differing frequencies. Noise probability density function (pdf) has also been changed in order to observe its effect on the reflection characteristics.

*4.1 Frequency Sweep for different conductivities*

Simulations for different conductivity values, and for SNR values has been given in Fig. 4.

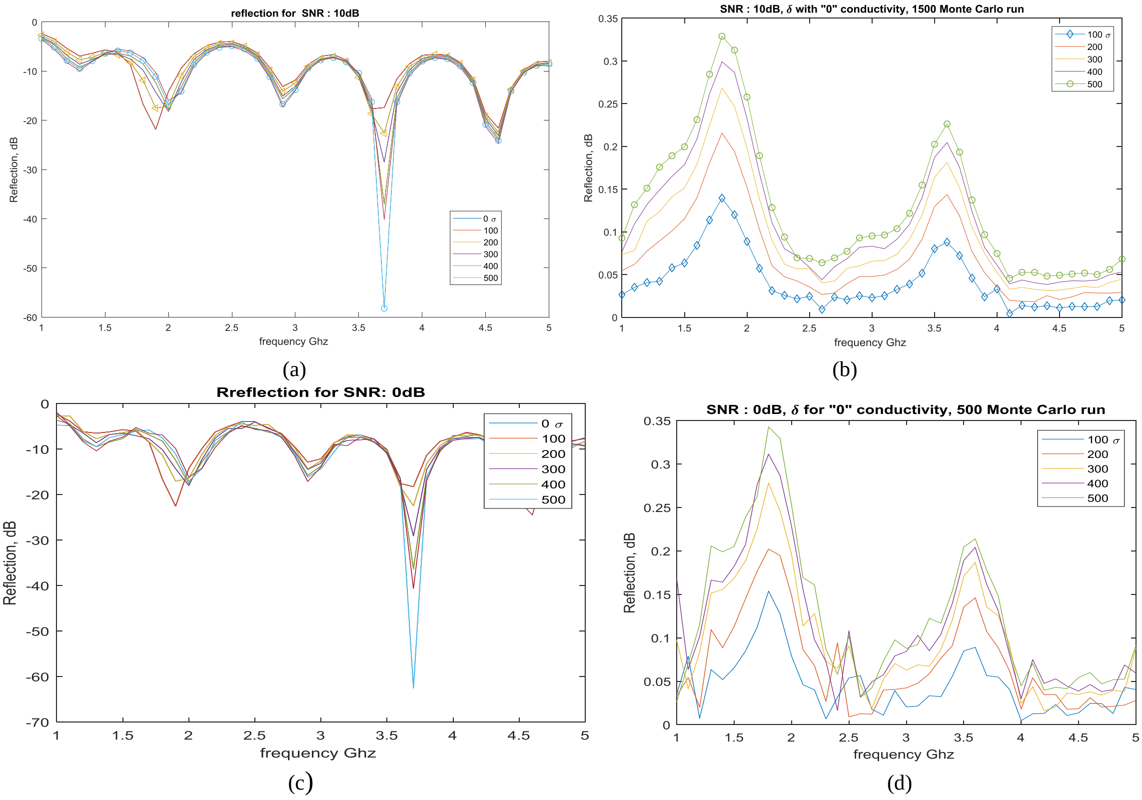


Fig. 4. Absolute Mean reflection and difference for Conductivity values

This simulation has been done for various *SNR* values. Monte Carlo runs are also changed *500 to 1500 f*or all simulations. In Fig. 4-a, while the frequency sweeps between *1Ghz-5 Ghz,* reflection coefficient has been observed for differing conductivity values from "*0" to "500"*

Delta ($\delta$) values plot for "*0*" conductivity with other values (*100,.., 500 µSiemens/m*) has been given in Fig. 4 (b), Fig. 4(d), with SNR values *0 dB* and *10 dB*

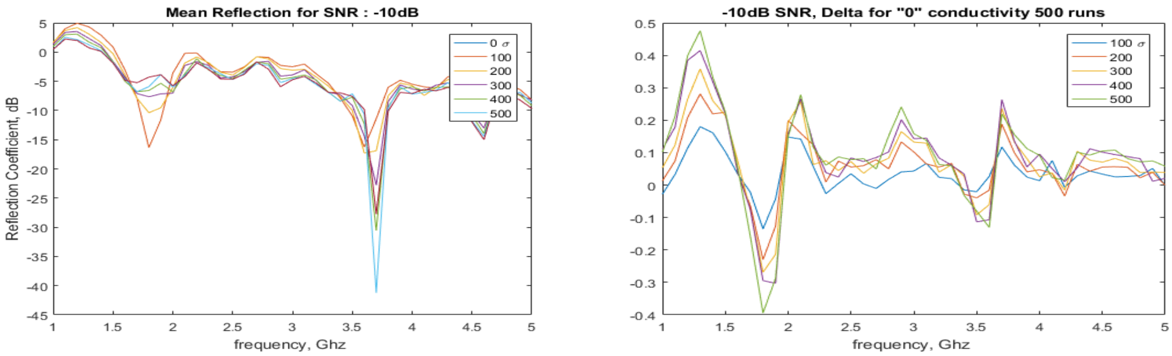


Fig. 5. Absolute Mean reflection and difference for conductivity values

It was interesting to see that even for $SNR = -10dB$, which means that the noise is stronger than the signal, for *500* Monte Carlo runs, we can detect meaningful values (Fig. 5).

In Fig. 4 and Fig. 5 it is clearly observed that the system has a sudden drop around *3.7* GHz. Observing difference delta signals with "0" conductivity, it is observed that there are two main distinctive frequencies; around *1.7*GHz and *3.7* GHz. This gives us an important information: If a peak has been observed at *3.7* GHz, responsible institute from the water quality shall be alarmed and take necessary actions to overcome a possible contamination.

### *4.2 Conductivity Sweep for different Frequencies*

Same configuration, now the conductivity value has been swept between 0-1000 µSiemens/m, while the frequency has been iterated from *3.5* GHz to *4.0* GHz with a step size of *0.1* GHz. For these simulations, Monte Carlo iterations have not been applied. Instead we repeated the iteration many times manually and observed that the mean characteristics of the plots did not change.

*4.3 Noise pdf: Normal (Gaussian), SNR changed:*

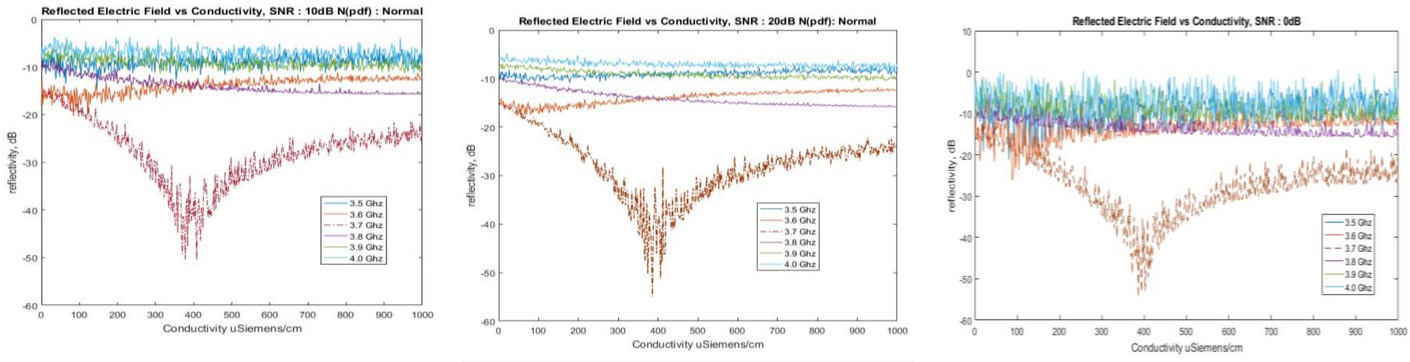


Fig. 6. Absolute Mean reflection and difference for conductivity values

*4.4 SNR Constant, Noise (pdf) changed*

This simulation has been done for fixed SNR values and Monte Carlo runs. In this simulations, pdf's of the noise has also been changed; Normal, Uniform Rayleigh (Fig. 7*)*. In these simulations, no significant change has been observed on the plots. However, future works can be carried in order to observe higher order moments (other than mean and variance, 3rd moment Skewness; and 4th moment Kurtosis) of the output histogram and some distinctive values can be observed on these moments.

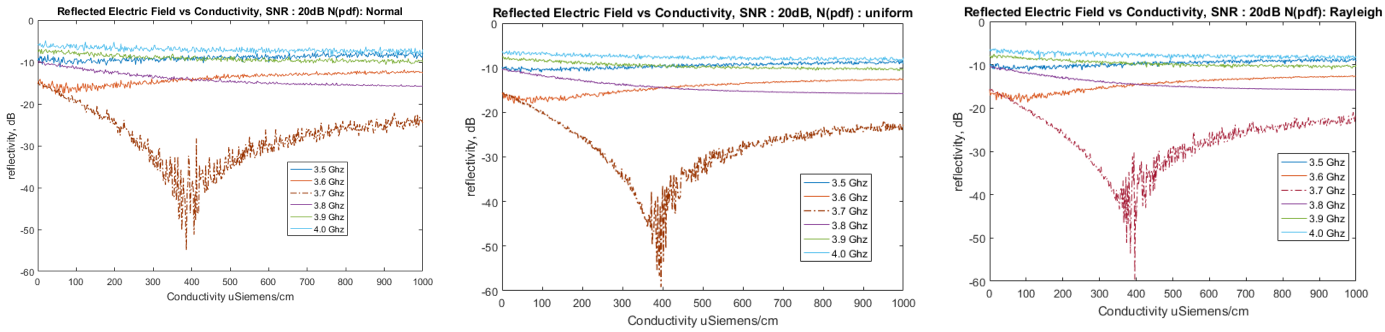


Fig. 7. Reflection Value for normal, uniform and Rayleigh pdf noise functions.

It is observed that for all these runs, for *3.7* GHz, there is a significant drop (about *30dB*) in the output reflection signal. This is a typical resonance frequency which is an indicator for the configuration given in Fig. 3. When the thickness of any layer or any property has been changed, this frequency value also shifts.

## 5. Conclusions

In this study we have introduced a multilayer analysis application with an EM Wave. We have modelled the ground with soil and water, and looking at the water layer conductivity change, we tried to predict possible water contamination.

For a sample configuration terrain with sample water layer and soil thicknesses, a specific frequency has been obtained, which gives a discrimination for specific conductivities. If we have chosen different thicknesses and electrical parameters other than given in Table 1, discriminative point and peaks differ. This can also be evaluated as follows; for those conductivities between *400-500* µSiemens/cm, applying an RF source with *3.7* GHz is a discriminative value.

In this study, deviations from the reference value more important than the value itself is. Since each terrain may have its own "*clean water reference*", we have also concentrated on the difference graphs with conductivities. In order to approach real systems, two types of noise has been added to the output reflection measurement. This noise mostly can be modeled as normal (*Gaussian*) but some different distribution functions like "*Rayleigh*" or "*Uniform*" can also be applied.

In the manuscript, sample plots has been given for assumed pdf's, but detailed plots with distribution functions, for each layer and thicknesses may be introduced depending on the terrain structure. The code permits any layer thickness, with any ambiguity pdf on any parameter, driven by source with any frequency.

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