# Water-filled testbed modeling, design, and fabrication for performance validation of a holographic subsurface RADAR antenna

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1st Luca Bossi
*Department of Information Engneering*
*Università degli Studi di Firenze*
Florence, Italy
l.bossi@unifi.it

2nd Pierluigi Falorni
*Department of Information Engneering*
*Università degli Studi di Firenze*
Florence, Italy
pfalorni@gmail.com

3rd Fronefield Crawford
*Department of Physics and Astronomy*
*Franklin and Marshall College*
Lancaster, PA, USA
ORCID: 0000-0002-2578-0360

4th Tim Bechtel
*Department of Earth and Environment*
*Franklin & Marshall College*
Lancaster, PA, USA
tbechtel@fandm.edu

5th Vadym Plakhtii
*School of Radio Physics, Biomedical Electronics, and Computer Systems*
*V.N. Karazin Kharkiv National University*
Kharkiv, Ukraine
plakhtii@karazin.ua

6th Lorenzo Capineri
*Department of Information Engneering*
*Università degli Studi di Firenze*
Florence, Italy
lorenzo.capineri@unifi.it

***Abstract*—The characterization of microwave subsurface holographic RADAR sensors is not simple because the investigated medium is generally not homogeneous, and the soil electromagnetic properties change with moisture content. Commonly, holographic radars designed for terrain investigations use sand-box testbeds. To ensure the homogeneity of the medium and a well-defined value of dielectric permittivity and conductivity (attenuation), we designed and fabricated a testbed filled with water. With a solution of Sodium Chloride concentration at room temperature, it is possible to obtain a specific dielectric permittivity and the desired attenuation. In this paper we describe the design process, the fabrication, and a preliminary experiment with distilled water using a plastic candy box as a target. This approach to the fabrication of a RADAR testbed guarantees the repeatability of the measurements reducing the number of uncontrolled variables in laboratory experiments.**

***Keywords—Testbed, saltwater dielectric permittivity, holographic subsurface radar, soil experiments, ground penetrating RADAR***

## I. Introduction

Holographic subsurface RADARs (HSRs) are used in many fields for obtaining microwave images of targets at shallow depths in soil. In our application, we use HSR to detect shallow-buried objects in conflict zones, and classify landmines or other explosive threats versus ubiquitous clutter [1], [2]. Recently, we designed an innovative plastic-filled, 3D-printed, waveguide HSR antenna [3] and carried out preliminary laboratory tests to compare its performance with a previous designs. [4]

The proposed investigated medium (soil), is generally inhomogeneous, with a dielectric permittivity that changes with moisture content that often varies between the layers of the soil, and with mineralogy and texture (e.g. clay, sand, gravel, etc.) [5]. These conditions present remarkable difficulties for characterizing the performance of HSRs - introducing many variables that are not easily controlled. Laboratory experiments generally use testbeds filled with sand. The sand moisture content is measurable, and the sand approximates a homogeneous medium. However, the use of sand presents difficulties in that the dielectric permittivity (which is affected by humidity) is not easily adjusted, and the high unit weight of sand makes it difficult to move the test bed.

We have researched the effects of the salinity of water on its dielectric permittivity in our frequency range of interest (1.5 GHz, 2.5 GHz) [6]–[8], modelled losses to evaluate the relation between the depth of the target and the attenuation of the medium, and built a plastic box that we have filled with water. The simulation was done by building a MATLAB® script based on the Stogryn Model [9]–[12].

## II. Theory

### A. Stogryn Model

Experimental evidence indicates that the dielectric constant of salt water as a function of frequency, water temperature and salinity, may be adequately represented by an equation of the Debye form

$$K = \varepsilon_\infty + \frac{\varepsilon_0 - \varepsilon_\infty}{1 - j2\pi\tau f} + j\frac{\sigma}{2\pi\varepsilon_0^* f} \qquad (1)$$

were $\varepsilon_0$ and $\varepsilon_\infty$ are, respectively, the static and high-frequency dielectric permittivity of distilled water (modified by the concentration of Sodium Chloride or NaCl), $\tau$ is the Relaxation Time, $\varepsilon_0^*$ is the dielectric permittivity of a vacuum ($8.854\ 10^{-12}$ F/m), $\sigma$ is the ionic conductivity of the salt water in mho/m, and $f$ the frequency of the electromagnetic wave.

The parameters $\varepsilon_0$, $\varepsilon_\infty$ and $\tau$ are related to these analytic expressions

$$\varepsilon_0(T,N) = \varepsilon_0(T,0)a(N) \qquad (2)$$

$$2\pi\tau(T,N) = 2\pi\tau(T,0)b(N,T) \qquad (3)$$

where T is the water temperature in °C, and N the normality of the solution. For $0 \le T \le 40\ °C$ and $0 \le N \le 3$

$$a(N) = 1 - 0.2551N + 5.151 \cdot 10^{-2}N^2 + -6.889 \cdot 10^{-3}N^3 \qquad (4)$$

$$b(N,T) = 0.1463 \cdot 10^{-2} NT + 1 - 0.04896N - 0.02967N^2 + +5.644 \cdot 10^{-3} N^3 \quad (5)$$

$$\varepsilon_0(T,0) = 87.74 - 4.0008T + 9.398 \cdot 10^{-4} T^2 + +1.410 \cdot 10^{-6} T^3 \quad (6)$$

$$2\pi\tau(T,0) = 1.1109 \cdot 10^{-10} - 3.824 \cdot 10^{-12} T + +6.938 \cdot 10^{-14} T^2 - 5.096 \cdot 10^{-16} T^3 \quad (7)$$

where $\tau$ has units of seconds. Finally, for the conductivity of the salt water

$$\sigma_{NaCl}(T,N) = \sigma_{NaCl}(25,N) \cdot (1 - 1.962 \cdot 10^{-2}\Delta + +8.08 \cdot 10^{-5}\Delta^2 - \Delta N \cdot [3.020 \cdot 10^{-5} + 3.922 \cdot 10^{-5}\Delta + N \cdot (1.721 \cdot 10^{-5} - 6.584 \cdot 10^{-6}\Delta)] \quad (8)$$

where $\Delta = 25 - T$ and

$$\sigma_{NaCl}(25,N) = N \cdot [10.394 - 2.3776N + 0.68258N^2 + -0.13538N^3 + 1.0086 \cdot 10^{-2} N^4]. \quad (9)$$

## III. Simulation model

The above equations were implemented in a MATLAB script that considers the frequency and the temperature of the water. We calculated the effects of different concentrations of NaCl in the distilled water at desired room temperature.

In Figure *1*, are reported the simulated values from the Stogryn model of water. This graph depicts the attenuation (in Decibels) of various saltwater solutions with increasing path length in the water. In the table are reported the NaCl concentrations corresponding to the colors of the attenuation curves. The attenuations are calculated for a temperature of 20°C and a frequency of 1.66 GHz.

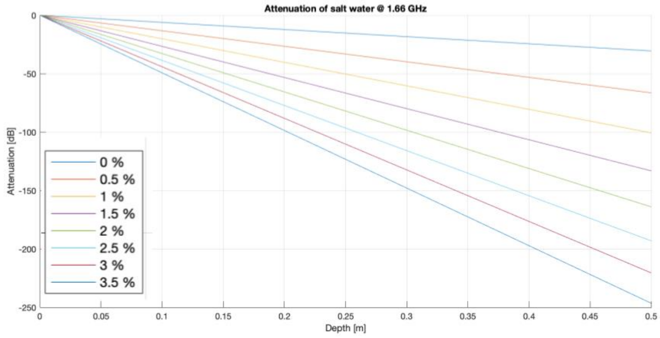


*Figure 1 - Simulation results from the Stogryn model of signal attenuation in relation to the distance of wave propagation in various saltwater solutions (see legend).*

A testbed is designed to have a controlled environment which may replicate the electromagnetic properties of minefields. The terrain considered as a reference is the chernozemic soils of the Donbass region in Ukraine where there is landmine contamination following recent and ongoing conflict. The Donbass soil can be approximated as wet loam [5]. Referring to Table 1 [13], we can choose a typical attenuation of 5 dB/m.

*Table 1 - D. J. Daniels, and Institution of Electrical Engineers, Eds.,* "Ground penetrating radar".

| Material | Attenuation, dB $m^{-1}$ | Relative permittivity range |
|---|---|---|
| Air | 0 | 1 |
| Asphalt dry | 2–15 | 2–4 |
| Asphalt wet | 2–20 | 6–12 |
| Clay dry | 10–50 | 2–6 |
| Clay wet | 20–100 | 5–40 |
| Coal dry | 1–10 | 3.5 |
| Coal wet | 2–20 | 8 |
| Concrete dry | 2–12 | 4–10 |
| Concrete wet | 10–25 | 10–20 |
| Freshwater | 0.01 | 81 |
| Freshwater ice | 0.1–2 | 4 |
| Granite dry | 0.5–3 | 5 |
| Granite wet | 2–5 | 7 |
| Limestone dry | 0.5–10 | 7 |
| Limestone wet | 1–20 | 8 |
| Permafrost | 0.1–5 | 4–8 |
| Rock salt dry | 0.01–1 | 4–7 |
| Sand dry | 0.01–1 | 2–6 |
| Sand wet | 0.5–5 | 10–30 |
| Sandstone dry | 2–10 | 2–5 |
| Sandstone wet | 4–20 | 5–10 |
| Sea water | 100 | 81 |
| Sea-water ice | 1–30 | 4–8 |
| Shale dry | 1–10 | 4–9 |
| Shale saturated | 5–30 | 9–16 |
| Snow firm | 0.1–2 | 6–12 |
| Soil clay dry | 0.3–3 | 4–10 |
| Soil clay wet | 5–50 | 10–30 |
| Soil loamy dry | 0.5–3 | 4–10 |
| Soil loamy wet | 1–6 | 10–30 |
| Soil sandy dry | 0.1–2 | 4–10 |
| Soil sandy wet | 1–5 | 10–30 |

Replicating the characteristics of the soil with a saltwater box, and using the salinity of the water to scale the dimensions of the box we can obtain some advantages:

- A light test bed that is easily transportable, with quick setup and disassembly.
- A flat surface having high dielectric contrast with air.
- Easy positioning of the target inside the medium (water) and replicability of measurement.
- The possibility to position the antenna aperture over the surface of the water to radiate only inside the medium.

## IV. Testbed fabrication

The specification for the testbed are the followings:

- About 100 dB attenuation of the reflected signal from the side and bottom plastic walls of the test bed.
- Water attenuation matching the attenuation of minefield soil.

To satisfy the requirements indicated by the simulation, we chose an NaCl concentration of 12 g/l.

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Figure 2 depicts the dimensions of the testbed. With this concentration of salt in the water, the dielectric permittivity of the water determines a reflection index of the water surface of about 9. In these conditions the reflection coefficient of the water-air interface is 0.64 and the wavelength of the transmitted 1.66 GHz RADAR signal in the water is about 2 cm.

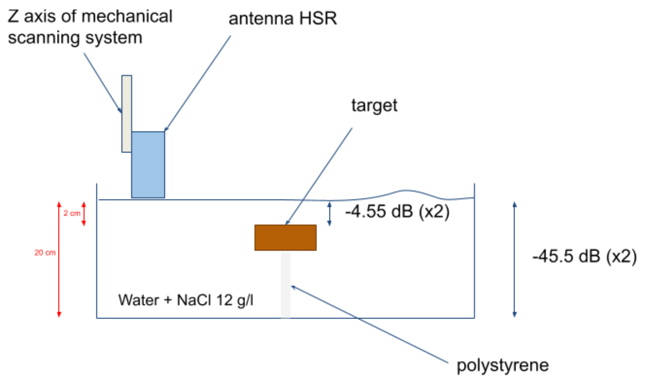


*Figure 2 - Design of water-filled testbed for simulating Donbass soil conditions. The values of attenuation are for water with 12 g/l concentration of NaCl, and the dimension of the testbed satisfy the attenuation requirements for side and bottom wall reflections.*

For the testbed structure we utilized a commercial plastic box as shown in Figure 3.


*Figure 3 - Image of commercial plastic box used for fabricating the testbed showing dimensions and volume.*

The first experimental setup with distilled water (@ 1.7 GHz, calculated complex dielectric permittivity is $\varepsilon_r = 79.35 + j7.38$) is shown schematically in Figure 4 (top) with the robotic scanning platform (named "Ugo 1st"), and plastic candy box, which we used as a reference, positioned in the water. The target is filled with epoxy resin and has a diameter of 7.5 cm, and height of 3 cm. Figure 4 (bottom) is a photograph of the fabricated box before the experiment.

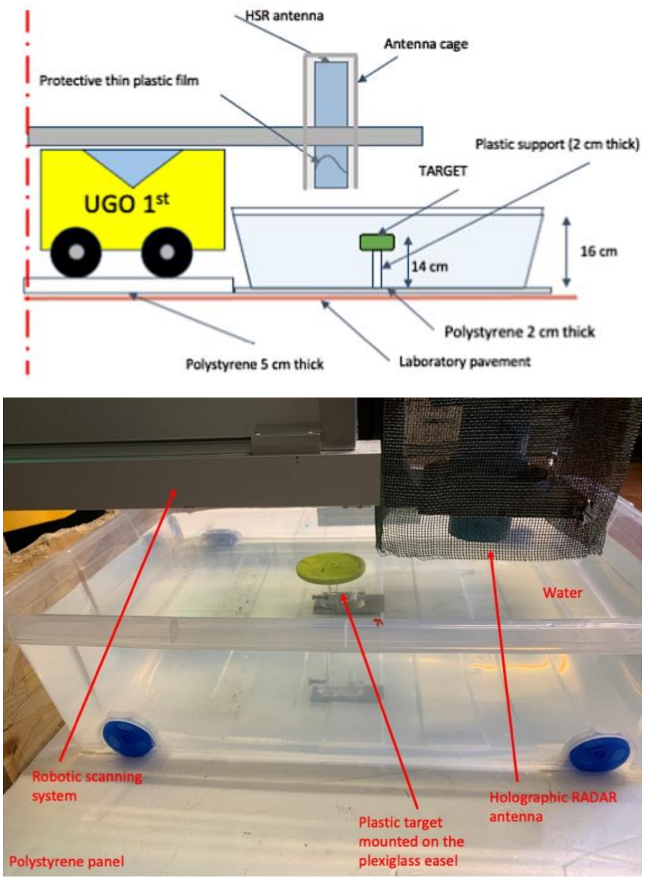


*Figure 4 - (Top) Drawing of the setup of the preliminary experiment with distilled water. (Bottom) A picture of the testbed, antenna and target inside the water.*

## V. Conclusions

We have demonstrated the design of a testbed for validation of a holographic RADAR system based on a plastic box filled with water. The possibility of obtaining a testbed that is easy to fabricate, versatile in terms of the dielectric permittivity and conductivity that can be easily varied by changing the NaCl concentration of the water, and the repeatability of the measurement conditions are the key advantages to this setup. The fabricated testbed was utilized for an initial set of experiments, with this work reported in a separate paper at this conference.

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