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ESTIMATION OF RELATIVE PERMITTIVITY OF SHALLOW SOILS BY USING THE GROUND PENETRATING RADAR RESPONSE FROM DIFFERENT BURIED TARGETS

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Abstract—Combined ground penetrating radar and metal detector equipment are now available (e.g., MINEHOUND, ERA Technology-Vallon GmbH) for landmine detection. The performance of the radar detector is influenced by the electromagnetic characteristics of the soil. In this paper we present an experimental procedure that uses the same equipment for the detection and calibration by means of signal processing procedures for the estimation of the relative permittivity

of the soil. The experimental uncertainties of this method are also reported.

1. INTRODUCTION

Ground penetrating radar (GPR) for landmine detection has reached the stage where portable equipment for field operations is commercially available. Dual sensor systems in which high performance metal detectors (MD) are combined with GPR have been extensively trialled [1–6].

The operating conditions for the GPR depend on the electromagnetic characteristics (magnetic susceptibility μ_R, conductivity σ and relative permittivity ε_R) of the soil. It has been shown that the relative permittivity changes in space and also in time [7, 8]. These variations are the main reasons why the GPR systems need either manual or auto-calibration before their use as a mine detector. Where systems provide an indication of burial depth of the target it is important that the propagation velocity is known for the soil under investigation and this paper addresses this issue.

The paper describes an assessment of methods that can be used by supervisory operators in the field for the estimation of ε_R of soil at shallow depth. This aim is also currently under discussion by the CEN WS7 [9]. The estimation of ε_R is obtained indirectly by the propagation velocity $v = c/\sqrt{\varepsilon_R}$, where c is the speed of light in vacuum.

Experiments were carried out at the test site of ERA Technology using the MINEHOUND$^{(\mathrm{TM})}$ dual sensor system jointly developed with Vallon GmbH for the MD unit. Different metal targets were buried at different depths in a soil defined as ballast.

2. EXPERIMENTAL MEASUREMENTS

2.1. Test Site

The test site at ERA Technology in Leatherhead comprises area 5 metres by 10 metres of depth 1 m of a mixture of pea gravel and sand to form a ballast soil. The nominal value of ε_R of this soil was estimated to be 5. All experiments were conducted in two consecutive days. During the second day the soil moisture was higher due to a rainfall in the night.

2.2. MINEHOUND Radar System Parameters

ITEM	VALUE
Internal pulse duration	240 ps at −6 dB, unipolar
Internal pulse amplitude	15 V peak
Pulse repetition frequencies	1 MHz
Bandwidth of operation	from 250 MHz to 2.5 GHz
EIRP†	< -41 dBm/MHz
Radar sampling	512 samples per scan
Receiver time range	19.2 ns
Receiver sampling interval	37.5 ps
Output scan rate	61 Hz
Sweep speed	$<1.5\,\mathrm{ms}^{-1}$
Output	Audio/Visual
Temperature	**from −32°C to 65°C**

2.3. Targets

A variety of targets can be used to enable the measurement of relative dielectric constant and these can be either metallic or dielectric. The following metallic targets were selected:

- A metal pipe 80 cm long, external diameter of 20 mm acquired during first day.
- A metal sphere, 70 mm diameter acquired during second day.

All these targets are low cost and are readily available in most countries, particularly for those in the Third World. Metal spheres can be found also as toy balls.

2.4. Radar Target Response

Material for all metal targets should be highly conductive metal (e.g., copper, iron, and chromium plated steel). Hollow pipes or spheres with metal thickness of at least 1 mm are also acceptable. The radar response depends on the target geometry, antenna configuration, frequency and soil properties. To compare the different targets response we report their Radar Cross Sections (RCS) expressions [10]. The calculations of the RCS for $\varepsilon_R = 1$ (air) and $\varepsilon_R = 5$ (soil) according to the dimensions of our targets at radar central frequency $f_C = 1$ GHz are reported in Table 1. The calculated RCSs are valid in the far field and diffraction effects from edges are neglected.

† Equivalent Isotropically Radiated Power

Table 1. Radar cross-section values of used targets.

Target	RCS ($\varepsilon_R = 1$, $\lambda = c/f_C = 0.3\,\text{m}$)	RCS ($\varepsilon_R = 5$, $\lambda = c/f_C = 0.13\,\text{m}$)	Parameters
1	0.1340	0.3	a radius $= 0.01\,\text{m}$ L length $= 0.8\,\text{m}$ ϑ angle broadside $= 0^\circ$
2	0.0038	0.0038	a radius $= 0.035\,\text{m}$
3	0.0707	0.3534	A plate area $= 0.0225\,\text{m}^2$

The pipe target, with the dimensions specified above, has the highest RCS with respect to the other targets. The flat plate has a high RCS but it strongly depends on λ and its radar response is very dependent on the actual incident angle of the transmitted beam: This is why we chose not to use it. When using linearly polarized dipole antennas, metallic pipes and low impedance dielectric pipes are best detected with the long axis of the dipole antennas oriented parallel to the long axis of the pipes and this should be specified in the measurement procedure. A sphere response is less dependent from radar antenna polarization and view angle.

For the aim of testing, it should be noted that the electrical properties of the soil will be changed by excavation and care is needed to replace and compact the soil when emplacing targets. A soil of the type used readily compacts after excavation and is thus ideal because its electrical characteristics soon revert to normal.

2.5. Measurement Technique

The targets were buried with the following depths of cover; 2 cm, 5 cm, 10 cm and 15 cm. In practice an uncertainty of few millimetres will be encountered at these nominal depths. To help the operator, the scanning was carried out with the radar sweeping in contact with the surface of a rectangular thin plastic layer (2 mm thick and $\varepsilon_R = 3$) placed over the soil, covering the area where the target was buried. This layer is thin enough so as to cause minimal effect on the measurements.

Longitudinal and transversal single scan were repeated along the plastic layer's orthogonal axis for both directions (left to right and right to left).

3. ELECTROMAGNETIC MODEL OF THE EXPERIMENT

The estimation of time of flight (TOF) has been done according to an electromagnetic model of the experiment. In a first approximation we can assume the radar operates in a monostatic mode at height h from the surface of the soil and the target as a point-like reflector. The ray path descriptions for the time-of flight calculations are shown in Figure 1. As the soil relative permittivity is unknown, the point y_B at the boundary between air and soil has to be estimated. In order to have an explicit solution for y_B we can consider that the limit position of the incident point is Y_1 when $\varepsilon_R = 1$ (soil=air) and is given by:

$$Y_1 = Y_S * Z_0/(Z_0 + h) \tag{1}$$

According to Snell law the approximate value of y_B assuming for a soil ε_R greater or equal to 1 is given by:

$$y_B = Y_1/\sqrt{\varepsilon_R} \tag{2}$$

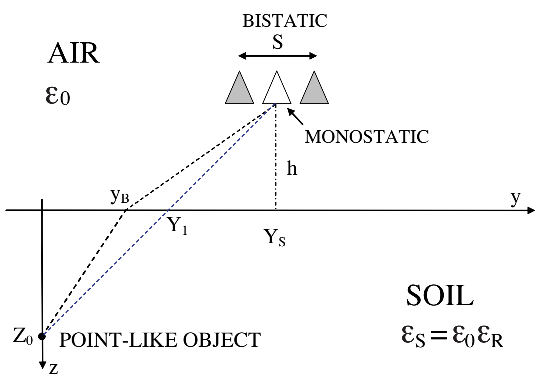

Figure 1. Snell approximation for incident beam at the interface between air-soil layers for the monostatic case.

Assuming that the previous approximations are valid, we can derive the explicit expression of minimum time-of-flight for the case of bistatic antennae, where S is the separation distance (see Figure 1). The minimum TOF is obtained when the radar is centered over the target ($Y_S = 0$).

$$TOF_{1\,\min} = \frac{2}{c}\sqrt{\left(\frac{S}{2}-\frac{S}{2}\frac{Z_0}{Z_0+h}\frac{1}{\sqrt{\varepsilon_R}}\right)^2+h^2} + \frac{2}{c}\sqrt{\varepsilon_R}\sqrt{\left(\frac{S}{2}\frac{Z_0}{Z_0+h}\frac{1}{\sqrt{\varepsilon_R}}\right)^2+Z_0^2} \quad (3)$$

The time-of-flight corresponding to the air-soil interface is:

$$TOF_2 = \frac{2}{c}\sqrt{\left(\frac{S}{2}\right)^2+h^2} \quad (4)$$

The difference between $TOF_{1\,\min}$ and TOF_2 can be experimentally measured and it corresponds to a non-linear expression of the relative permittivity (the unknown parameter). The parameter h is not constant in real experiments besides an operator can be trained to minimize its variability. Moreover in real operating conditions the values of S, Z_0 and h are comparable and simplification of the expression is impossible. In Table 2 we calculated the time difference $\Delta T(h) = TOF_2 - TOF_{1\,\min}$ for $h = 2\,\text{cm}$ and $h = 10\,\text{cm}$ by using Equations (3) and (4). The difference $\Delta T(2\,\text{cm}) - \Delta T(10\,\text{cm})$ is evaluated and shown for two different values of ε_R. For this analysis we assumed the target depths used for the experiments.

Table 2. Variation of time-of-flight difference $\Delta T(2\,\text{cm}) - \Delta T(10\,\text{cm})$.

Soil relative permittivity ε_R	Target depth			
	$Z_0 = 2\,\text{cm}$	$Z_0 = 5\,\text{cm}$	$Z_0 = 10\,\text{cm}$	$Z_0 = 15\,\text{cm}$
5	20 ps	41 ps	50 ps	62 ps
3	26 ps	53 ps	70 ps	72 ps

The results of this analysis shows that the time of flight difference is always less than 100 ps and for some cases (see cells with grey background) is less than 50 ps. Therefore the influence of the antenna height cannot be neglected in the general case.

4. ESTIMATION OF SOIL RELATIVE PERMITTIVITY

The evaluation of the soil relative permittivity ε_R has been done by measuring the difference between $TOF_{1\,\min}$ and TOF_2 with the data for the metal pipe and for the metal sphere. For both we considered minimum $h = 2\,\text{cm}$ and maximum $h = 10\,\text{cm}$.

The minimum of the time difference was calculated by searching the maximum detection trace among the data set. Without an explicit solution for ε_R, we have applied a numerical estimation by using Matlab routines.

The target detector is based on the hypothesis that the signal reflected by the target is similar to the signal reflected by the air-ground interface. The similarity check is made by using the linearity property of the cross correlation operator, like in (5), where s_{BG} is the signal reflected by the air-ground interface, s_T the signal reflected by the target and s the signal under investigation.

$$s_{BG} \cdot s_T = s_{BG} \cdot [s - s_{BG}] = s \cdot s_{BG} - s_{BG} \cdot s_{BG} \tag{5}$$

The amplitude of the expression in formula (5) can be evaluated by using its envelope (Hilbert transform). The maximum value of the amplitude of the function in formula (5) is upper limited by the maximum value of the autocorrelation (energy) of the signal s_{BG}; this is because in GPR experiments the energy carried by the target is always smaller than the energy carried by the air-ground interface. Therefore, the detector operates normalising the cross correlation in formula (5) to the maximum value of the auto correlation of the signal s_{BG} to get a relative estimate, like in formula (6).

$$\frac{|hilbert\,(s \cdot s_{BG} - s_{BG} \cdot s_{BG})|}{\max\{s_{BG} \cdot s_{BG}\}} \tag{6}$$

A good estimator of $\Delta T(h)$ is the lag of the maximum value of the amplitude of the cross correlation between the air-ground reflection signal and the target reflection signal is given by:

$$\Delta T(h) = \arg\max\{|hilbert\,(s \cdot s_{BG} - s_{BG} \cdot s_{BG})|\} \tag{7}$$

5. RESULTS

The evaluation of the mean soil ε_R according to the propagation model for a bistatic antenna is within the standard deviation to the expected value of relative dielectric constant for the ballast of 5.

The larger standard deviation of the pipe was due to one corrupted measurement that is relative to the smaller depth (2 cm). Avoiding this value we calculated a Mean (ε_R) of 3.98 and standard deviation of 0.48.

Table 3. Measured results.

Target	Depth = 2 cm		Depth = 10 cm	
	Measured value	**Standard** bf Deviation	**Measured value**	**Standard Deviation**
Pipe	4.81	1.7	4.34	0.4
Sphere	4.35	1.56	3.92	0.25

6. CONCLUSIONS

There is a trend that suggests that the measurements of relative dielectric constant report higher values for shallower targets. Although these results are satisfactory, the authors are investigating other methods and targets as a means of improving the accuracy of the measurement procedure. We are also considering additional signal processing to the remove the direct coupling between the two antennas.

The main source of error in the method is given by the usage of the cross correlation operator that worsen the resolution of the inspected signals.

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