IMEKO International Conference on
Metrology for The Sea
Naples, Italy, October 11-13, 2017

Dielectric constant determination using bistatic ground-penetrating radar: a case study at the Colombaia marine archeological area, Trapani, Italy

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Abstract – **The ground penetrating radar geophysical method is a rapid, high-resolution tool for non-invasive investigation. Ground penetrating radar records microwave radiation that passes through the ground and is returned to the surface. The radar waves propagate at velocities that are dependent upon the dielectric constant of the subsurface. Higher frequency sources will offer greater vertical resolution of structure but will not penetrate as deep as lower frequency sources.**

A method to determine ground-penetrating radar GPR velocities consist of determines the relative dielectric constant ratio at interface boundaries where the radar wave is traveling from a low-velocity to a high-velocity medium. Using Bistatic configuration and picking of the first arrivals we can determine the radar wave velocity in the medium. Our case study at the Colombaia marine archeological area demonstrated good repeatability and correspondence with subsoil material.

I. INTRODUCTION

Recent advances in technology and practice allow geophysical surveys in archaeology to produce maps of subsurface features over large areas and with great detail.

Ground-penetrating radar is a near-surface geophysical technique that allows archaeologists to discover and map buried archaeological features for landscape analysis in ways not possible using traditional field methods.

It is the most widely used near-surface geophysical method to produce three-dimensional images and maps of the ground.

The GPR method involves microwave radiation that passes through the ground and is returned to the surface. A transmitter sends a microwave signal into the subsurface, and the radar waves propagate at velocities that are dependent upon the dielectric constant (also known as relative permittivity) of the subsurface medium. Changes in the dielectric constant that are due to changes in the subsurface materials cause the radar waves to reflect, and the time it takes energy to return to the surface relates to the depth at which the energy was reflected [1].

The discontinuities where reflections occur are usually created by changes in electrical properties of the sediment or soil, lithologic changes, differences in bulk density at stratigraphic interfaces and most important water content variations. Reflection can also occur at interfaces between anomalous archaeological features and the surrounding soil or sediment. Void spaces in the ground, which may be encountered in burials, tombs, or tunnels will also generate significant radar reflections due to a significant change in radar wave velocity.

The depth to which radar energy can penetrate and the amount of definition that can be expected in the subsurface is partially controlled by the frequency of the radar energy transmitted. Radar energy frequency controls both the wavelength of the propagating wave and the amount of weakening, or attenuation, of the waves in the ground. Standard GPR antennas used in archaeology propagate radar energy that varies in band width from about 10 megahertz (MHz) to 1200 MHz.

One of the most important variables in GPR surveys is the selection of antennas with the correct operating frequency for the depth necessary and the resolution of the features of interest.

In this work we performed an electromagnetic characterization by bistatic GPR survey of the deposits placed at the sea level in the Colombaia marine archeological area.

Colombaia, also known as Peliade Tower or Sea Castle (figure 1), is an ancient medieval Trapanese fortress, set on an island at the eastern of Trapani Port. It is 32 meters high, consisting of four floors superimposed, with the first used as a tank, while the original entrance was on the second floor. It is one of the best examples of military architecture in Sicily.

In several periods the castle has undergone several transformations in particular by filling with sand and other materials.

Using two separate antennas, the survey was planned to know exactly the EM velocity structure of the shallow subsurface; it is important in identifying electrical properties of different reflectors. The electrical properties are related to the composition of the reflectors.

Fig. 1:Ortophoto image of Colombaia marine archeological area

II. DATA COLLECTION

The GPR survey is carried out using the GPR 100 MHz (centre frequency) antennas manufactured by Geophysical Survey Systems Inc. (GSSI) [2].

The following acquisition parameters were selected:

- samples per scan: 16384;
- scans for second: 10;
- channel: 1.

For the acquisition, a bistatic mode is applied, so the Tx and Rx antennas are separate of an offset that isn't constant during the acquisition.

In our bistatic radar systems, the transmitter is fixed at a certain position and the receiver is moved, along the profile, with a sampling step of 0,25 meters.

The minimum offset between the Tx and Rx antennas are 1,25 meters, the maximum is 11 meters. In particular, we adopted the Wide-angle reflection and refraction (WARR) configuration (figure 2). The transmitter is kept at a fixed location and the receiver is towed away at increasing offsets. As the relative positions of the antennae are known at all time, and hence the distances between them, it is a simple matter to calculate the mean radiowave velocity of the appropriate raypath. WARR surveys are normally used to estimate the subsurface velocity structure by analyzing the dependence of arrival time on offset for events reflected from subsurface horizons. In this survey type, the direct ground wave arrival time is zero at the 0 m antenna offset and for a laterally homogeneous media it increases linearly with increasing antenna offset. This variation between different antenna offsets and ground wave travel times is referred to as the time–offset relationship.

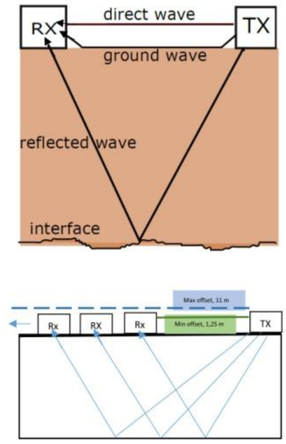

Fig. 2. UP: Bistatic GPR instrumentation includes two separate transmitting and receiving antennae units. DOWN: Schematic diagram to represent the WARR survey type.

III. DATA PROCESSING

The interpretation of GPR data is affected by many factors related to the complexity of the subsurface. The data interpretation requires dense grids of measurements, optimum choice of transmitting frequency and effective signal processing techniques.

To obtain more accurate information, the radar signals can be enhanced by digital data processing techniques, similar to those used in reflection seismic.

The GPR data processing system consists of time-zero corrections, dewow, background removal and other advances processes.

Drift of the zero time along the profile can occur due to temperature differences between the instrument electronics and the air temperature, or as a result of damaged cables. This drift causes a misalignment of the reflections and the zero time has to be reset for all traces along the profile.

Dewow removes the low frequency harmonics caused by electromagnetic induction [3].

The filter called "background removal" is a simple arithmetic process that sums all the amplitudes of reflections that were recorded at the same time along a profile and divides by the number of traces summed. The resulting composite digital wave, which is an average of all background noise, is then subtracted from the data set.

In our case study, after applying the basic processing, we did stacking, picking and analysis velocity.

Stacking consists of a synchronous signal summing which serves to reduce the noise associated to reflected wave and to attenuate multiples. Noise reduction is achieved by averaging more consecutive tracks and recording the average track.

Stacking allows to create a single trace from n traces of GPR data. Theoretically, the signal-to-noise ratio of the stacked profile is improved $\sqrt{n}$ times over the random noise when the number of traces of is n [4].

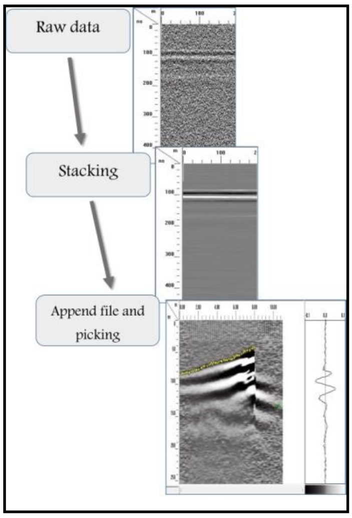

Fig. 3. Processing sequence.

Picking processes can be used to facilitate interpretation and to recover several parameters and attributes from the recorded profile, most importantly the reflected amplitudes and the two-way traveltimes, which can then be used to estimate the dielectric constant in the subsurface [5].

Picking of the leading edge transition of the direct ground wave event directly in a GPR trace is often difficult, but the peak of the ground wave event is relatively easy to identify and pick.

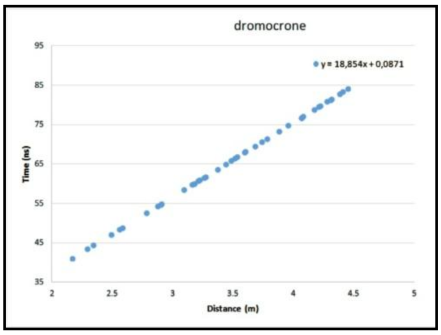

Fig. 4. Time-Distance graph. The inverse slope of the time–offset relationship gives the average ground wave velocity between the minimum and maximum antenna offsets

IV. DISCUSSION

A method to estimate the dielectric constant of the shallow subsurface using a GSSI 100 MHz GPR Bistatic antennas was presented. The local average dielectric constant was obtained via velocity analysis of GPR data acquired with WARR survey type, in which the transmitter antenna is kept at a fixed location while the receiver antenna is moved away from the transmitter at a constant spatial increment (Figure 1b). GPR WARR geometry results in gather of traces (figure 3) that have been processed using a standard seismic data processing sequence. To calculate the direct ground wave velocity, the direct ground wavelet were picked manually.

The picked travel times resulted in a velocity of 0.053 m/ns.

The propagation velocity (v) through the material is approximated using the following relationship (see full formula [6]):

$$v = \frac{c}{\sqrt{\epsilon_r}} \quad (1)$$

where where c is the electromagnetic wave velocity in vacuum (0.3 m/ns), ε_r the dielectric permittivity.

The equation (1) shows that the materials in the study area correspond to a dielectric constant of 32.03.

A simplified dielectric-lithology association (table 1) and direct observations of the outcropping formations, suggest that the subsurface was mainly composed by saturated sand deposits. Observing the Time-Distance graph, it is also assumed that the material proprieties are uniform and that the reflector characteristics are the same over the subsurface area over which the WARR sounding is undertaken

Table 1. Relative dielectric constant and radiowave velocities for a range of geological materials[XX, XX, XX, XX].

Material	ε_r	V (m/ns)
Air	1	0.3
Water	81	0.033
Sand (dry)	3-6	0.120-0.170
Sand (wet)	25-30	0.055-0.060
Silt (wet)	10	0.095
Clay (wet)	8-15	0.086-0.110
Clay (dry)	3	0.173
Granite	5-8	0.106-0.120
Limestone	7-9	0.100-0.113
Sandstone (wet)	6	0.112

In this paper we have described a tool to obtain the precise subsurface velocity determination. We believe that the WARR survey type may be especially useful in coastal archeological area providing constraints on the environmental setting of the terrain and giving important archaeological and historical information precisely, without compromising the physical integrity of the cultural heritage.

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