A STEPPED FREQUENCY GPR SYSTEM WORKING BOTH IN UNGATED AND GATED MODE

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ABSTRACT

In the framework of ARCHEO, a national research project funded by the Italian Ministry for Universities and Scientific and Technological Research (MURST), a new ground penetrating radar (GPR) has been developed by the Italian Consortium for Research on Advanced Remote Sensing Systems (CO.RI.S.T.A.). The system has been specially designed to match archaeological requirements and it will be used to identify and characterise buried finds.
The system is a ultra wide band (UWB) stepped frequency Ground Penetrating Radar (GPR) (Alberti et al., 2000a) able to work within a wide band of frequencies both in gated and ungated mode (Alberti et al., 2000b). The radar has been fully tested and characterised in the CO.RI.S.T.A.'s laboratory (Alberti et al., 2000b) before performing validation campaign on actual archaeological sites. In addition a dedicated outdoor test facilities has been designed and realised for calibrating the system and assessing its reference performance in a controlled environment. This paper mostly shows the preliminary results of the test campaign performed outdoor.

1. INTRODUCTION

The subject of electromagnetic prospecting by GPR is well known (Daniels D. J., 1996), and the possibilities offered by a GPR system have been shown in a huge amount of works, mainly focused either on the hardware of the system (Stickley G. F. et al., 1996) (Koppenjan S. K. et al., 1999), on the GPR data processing (Lehmann F. and Green A. G., 2000) and, maybe most of them, on the obtained results (Colla C. et al., 1995) (Ferruccio da Rocha P. L. et al., 2000) (Jol H. M. et al., 2000) (Meglich T. M., 2000) (Gao L., 2000). This paper is mainly aimed to show the preliminary results obtained outdoor by making use the UWB stepped frequency GPR system conceived in the framework of the project ARCHEO, financed by Italian MURST (Contratto di Ricerca 179201-1325/458, 1996). Let us only outline that the last is a big research project within it also other instruments, complementary to the GPR have been realised and tested (Fiorani L. et al., 2000a) (Fiorani L. et al., 2000b), within a multidisciplinary approach to the subject of the underground prospecting of which there are quite few examples in literature (Pipan M., 2000) and devoted to match possible archaeological needs.
The system has been realised within the laboratory of CO.RI.S.T.A in Naples where it has been also fully tested and characterised (Alberti et al., 2000b). Its stepped frequency working mode, can be regarded as innovative in spite of the fact that the advantages available from it are known since the seventies (Robinson L., 1974), because its diffusion in the world keeps being very low.
The radar can work both in ungated and gated mode, in order to have the possibility of reducing the coupling between the transmitting and receiving antennas offered by the gated mode but, if needed, to keep the possibility to exploit the greater dynamic range offered by the ungated mode due to the

absence of a duty cycle lower than 1 (Stickley G. F. et al., 1996) (Koppenjan S. K. et al., 1999) (Noon D. A., 1996).
In this paper we recall the main characteristics of the system and expose some results of a measurement campaign performed in a controlled site near Capua (Southern Italy), wherein a pool filled up with sand has been appositely realised outdoor and several test targets, both of dielectric and metallic nature at various depths, have been buried. While performing the campaign measurement, also an impulsive GPR system (courtesy of STRAGO s.r.l.) has been made use of for validation purposes. A preliminary and only qualitative analysis show that the new stepped frequency GPR reaches, in most cases, better performances by providing clearer images. ARCHEO project will be ended by gathering data over an actual archaeological site (Cales, near Capua, southern Italy) that will constitute the final validation of the radar system.

2. SYSTEM ARCHITECTURE

Following the same setting out of section 2 of Alberti et al., 2000b, in this section the architecture of the system is shown and described by dealing separately with the ungated and the gated modes, which should turn out in a simpler reading. Before, however, the reader is suggested to glance at the overall block diagram of the system, given in figure 1.
In any working modes, an advanced VXI A/D converter acquires the received signal with 18 effective bits, while the whole system is controlled by a VXI computer by means of software developed under LabView. The main characteristics of the system are summarised in table 1.

2.1 Ungated mode

In the ungated mode, the two frequency synthesisers Tx and Rx of figure 1 generate two tones with a frequency difference of 1 MHz, whereas the coherent oscillator (COHO) is not active. Therefore, the received signal bypasses the mixers R1 and S1 and the filters R1 and S1, further than the COHO itself. A little part (the tenth part in terms of power) of the signal generated by the Tx transmitter is picked up by a directional coupler and is mixed (S2 mixer) with half of the signal generated by the Rx synthesiser, through the power splitter shown in figure 1. Analogously, the signal received by the Rx antenna is combined, by means of the mixer R2, with the other half of the signal generated by the Rx synthesiser. The rejection of high frequency components is accomplished by the filters S2 and R2 that produce in output two tones at 1 MHz, whose phase difference is related to the electrical path of the signal into the soil (once the electrical path inside the system be excluded by calibration).
The sampling clock (3 MHz) is implemented by a frequency triplication followed by a threshold device, both included in the timing system. This digital signal allows to pick up three samples out of a period of the final 1 MHz at the output of the filter R2, and this for each of the radiated frequencies. The obtained discrete data can be stored after a possible averaging and an inverse FFT can provide the response to the radiated synthetic pulse (Alberti et al., 2000a and 2000b).

2.2 Gated mode

In the gated mode the reception is inhibited while radiating the signal and the radiating is inhibited while receiving (Stickley G. F. et al., 1996) (Noon D. A., 1996). This is performed by a switch signal provided by the computer and synchronised with the COHO at 100 MHz. In gated mode the two synthesisers produce two tones with a frequency difference of 101 MHz whose values are reconstructed in the reception after the first mixing and filtering step (mixer, switch and filter R1 and S1 in figure 1) in both the receiving and synchronism chains.

Following the signals are mixed again with the tone at 100 MHz provided by the COHO and filtered by the same components used in the ungated mode (R2 and S2 filters). The two tones at 1 MHz are sampled, processed and stored likewise the ungated mode.

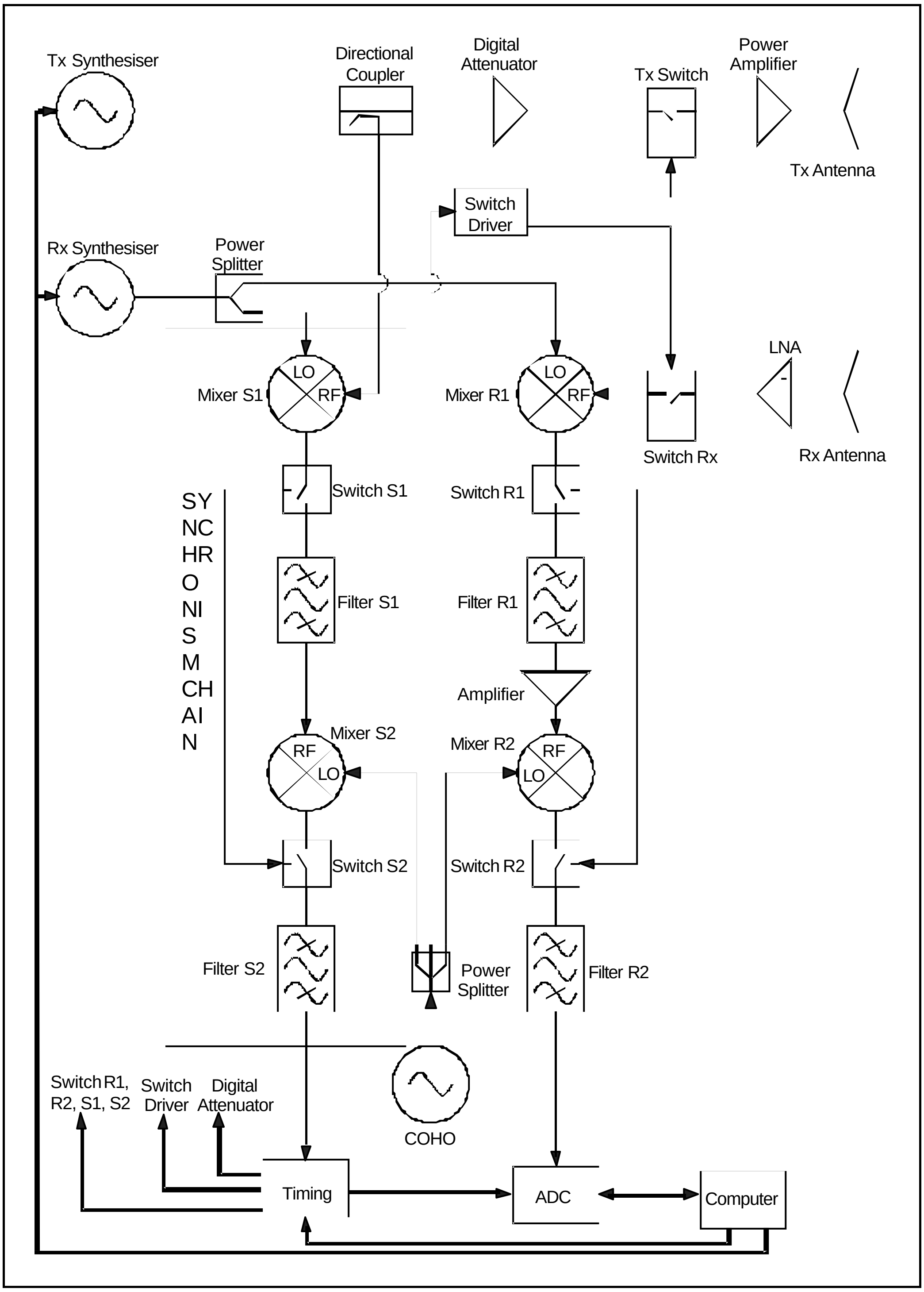

Figure 1: block diagram of the system

Type	Bistatic stepped-frequency	Transmitted power	5 W
Transmitted band	100-900 MHz	Positioning system size	320x320x100 cm^3
Intermediate frequency	1 MHz	Pulse length	> 100 μsec
COHO frequency	100 MHz	Antennas	Log-spirals
Resolution of the ADC	23 bit	ADC's dynamic range	> 100 dB

Table 1: main characteristics of the system

3. EXPERIMENTAL RESULTS

In order to calibrate the system and assess its performances in a reference and controlled environment, a dedicated outdoor test facility has been realised. In the framework of an agreement with the Italian Aerospace Research Centre (C.I.R.A.) located in Capua (southern Italy) and within its establishment, a 25x25 m^2 pool with a depth of 5 m has been build up and filled with river sand. Several objects, such as metallic sheets, plastic pipes, and tanks at different depth have been buried to be reference targets for the GPR system.

A portion of the pool as well as the experimental set-up of the stepped frequency GPR are shown in figs. 2 and 3. The first figure shows the rack (within the van) where the whole radar system is accommodated while figure 3 gives a particular of the antennas positioning system realised for the radar system. The antennas, the two blue short cylinders in figure 3, are log-spirals of about 40 cm of diameter (Alberti et al., 2000). The positioning system is essentially constituted by a mechanical structure able to keep the antennas and move them independently along three dimension paths, by means of three stepped motors. Let us note that such a system avoids the dragging of the antennas along the soil with their consequent progressive damaging while allowing the contact between the antennas and the soil when the electromagnetic waves are radiated and received. In addition, the antennas positions at any scan can be known within the uncertainty of few centimetres.

In figure 4 the image of a metallic sheet (1x2 m^2 wide) placed at 50 cm of depth is shown. The vertical axis represents the time, in seconds, with respect to the equivalent synthetic pulse, whereas the horizontal axis is the spatial co-ordinate expressed in actual scans. The transmitting and receiving antennas have been moved in linear common offset (Daniels D. J., 1996) along the direction orthogonal to the shorter side of the sheet and by keeping a distance of 55 cm between the antennas. This distance has been kept unchanged for all the measurements described in the present paper and it is the result of a trade-off between the levels of the direct antenna leakage and the received signal. The measurements of figure 4 have been started at 110 cm before the sheet edge and have been moved into 12 subsequent scan with a step of 20 centimetres. At any position, the frequency band transmitted was from 200 up to 800 MHz with a frequency step of 2 MHz. The GPR has worked in ungated mode. Let us note that no particular signal processing (Daniels D. J., 1996) (Lehmann F. and Green A. G., 2000) (Conyers L. B. and Goodman D., 1997) has been applied to the GPR data, apart the mandatory IFFT to get the synthetic pulses from the data gathered in the frequency domain (Noon D. A., 1996).

In figure 5 the image of the same metallic sheet, but deeper buried (1.2 m), is shown. The modality of the scan has kept unchanged with respect to the previous scan with the only differences that 14 scans have been performed and the measure has started about 60 cm before the sheet edge.

Actually, this time the sheet (evidenced by a rectangular frame) appears as a weaker signal with respect to the direct coupling signal between the antennas, that evidences a sort of false layer at the temporal depth of 10 ns wherein a ghost target toward the right hand side is particularly evident. This did not happen with the shallower sheet because the stronger returns from the target covered the coupling signal (the map of colours refers always to a normalised graph). In this case a scan in

gated mode can be helpful, because it should allow to avoid just the false returns due to the direct coupling between transmitting and receiving antenna.
The result of a B-scan in gated mode on the same target is shown in figure 6, wherein the false targets due to the coupling disappear. The B-scan has been performed on 10 spatial positions, stepped of 25 cm from each other. The gated mode has been implemented by considering 10 non-overlapping layers of 10 ns each all together and then by retaining the comprehensive response of the seven deeper layers.
Moreover, in figure 7 a B-scan on a metallic pipe is shown. The measures have been taken in 10 subsequent position, starting 135 cm before the pipe, that is at 80 cm of depth and it has a diameter of 80 cm and is about 1 metre long. It is placed underground with its axis parallel to the air soil interface and the system has exploited the ungated mode. The object is clearly visible, and the strength of the signal returned from it masks the coupling signal.
The results of a scan performed on a couple of pipes parallel to each other and with the axis parallel to the interface between air and soil are shown in figure 8. The two pipes (evidenced by rectangular frames) are made of plastic and are empty. Their depth is 85 cm, they are 3 m long and have a diameter of 40 cm and their axes are distant 60 cm. Actually one of the two pipes is clearly visible, whereas the other one gives a weaker (although well individuated) return. This unexpected difference can be due to the presence of the bound of the pool that can interacts with the incident field and provide a stronger return from the pipe placed on the hand right side.

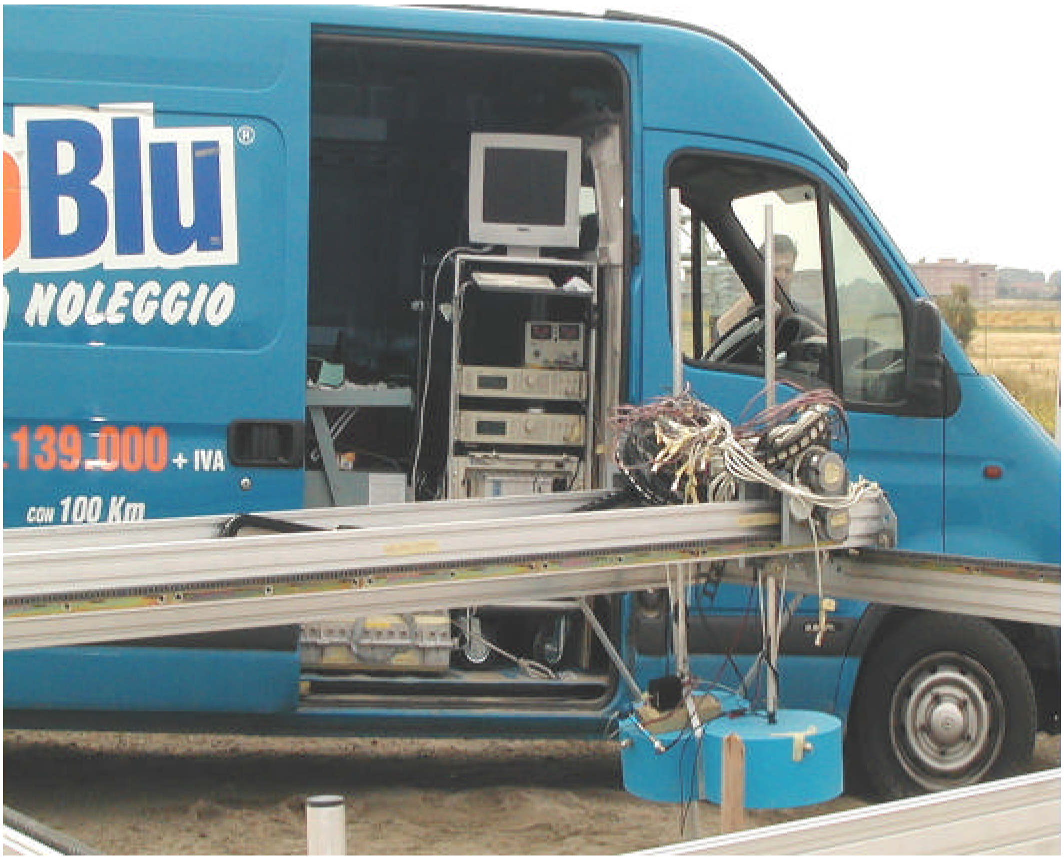

Figure 2: the rack of the GPR inside the van during data acquisition campaign

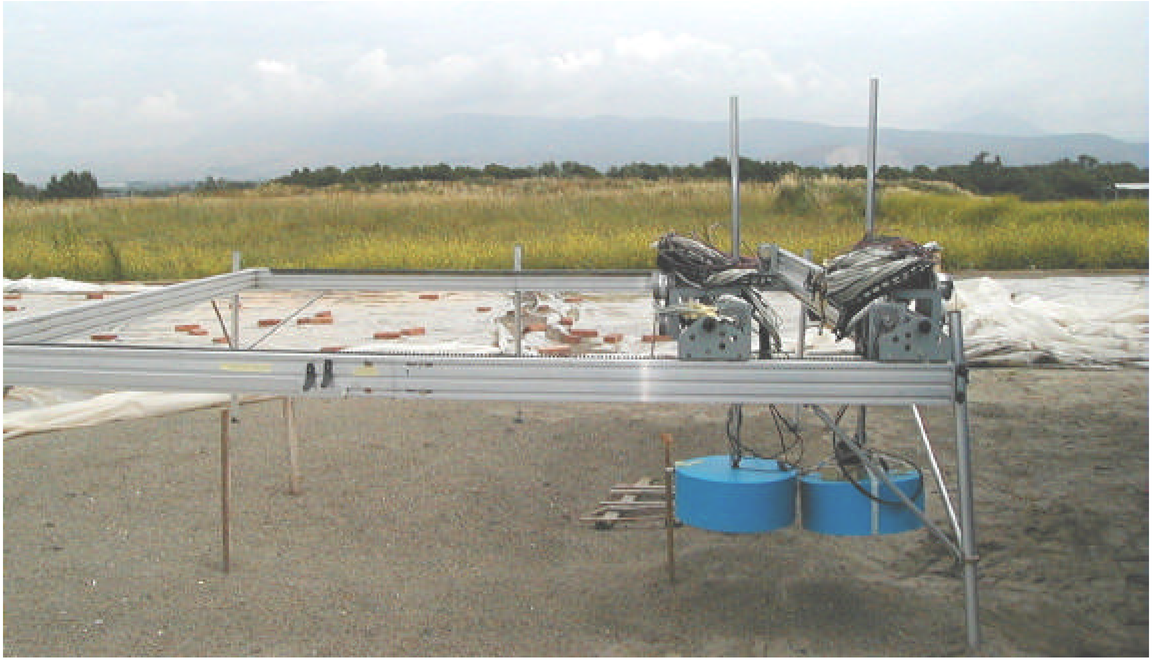

Figure 3: the antennas positioning system

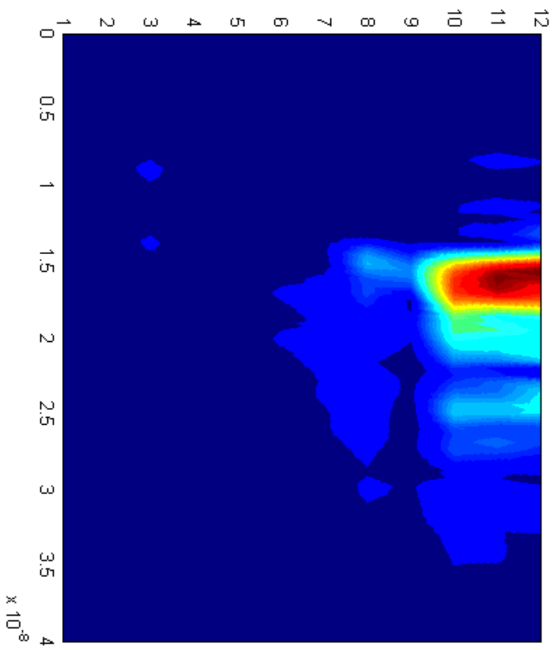

Figure 4: metal sheet at 50 cm of depth (ungated mode)

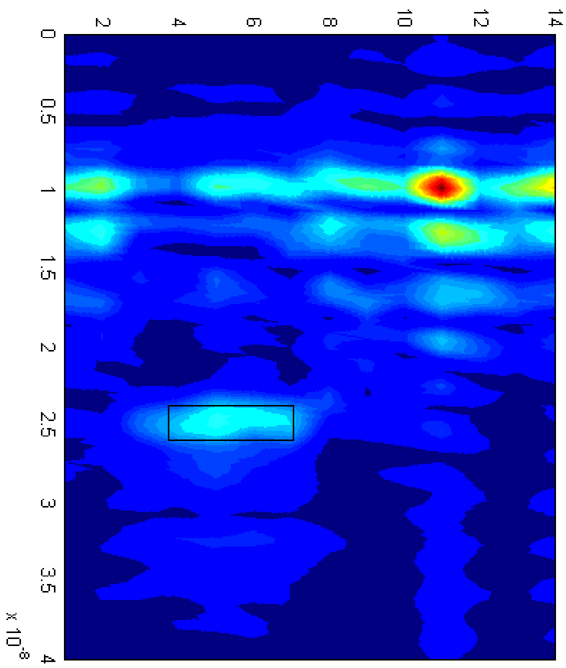

Figure 5: metal sheet at 120 cm of depth (ungated mode)

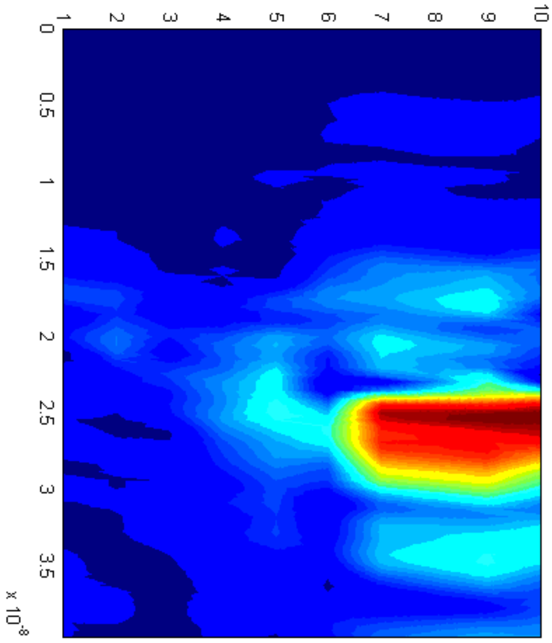

Figure 6: metal sheet at 120 cm of depth (gated mode)

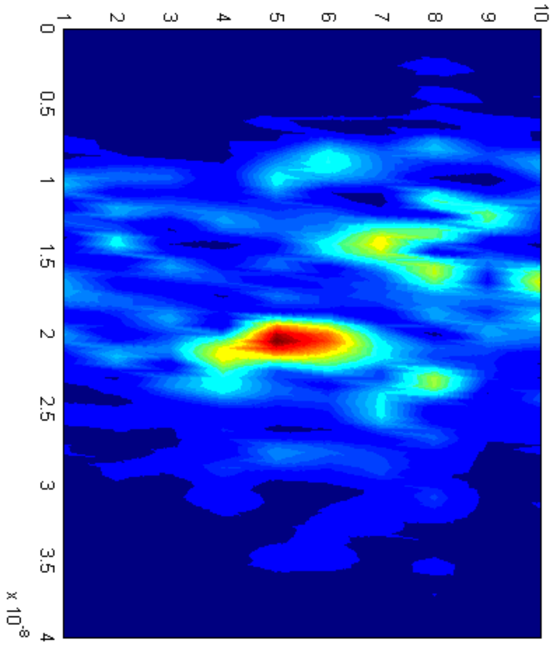

Figure 7: metal pipe at 80 cm of depth (ungated mode)

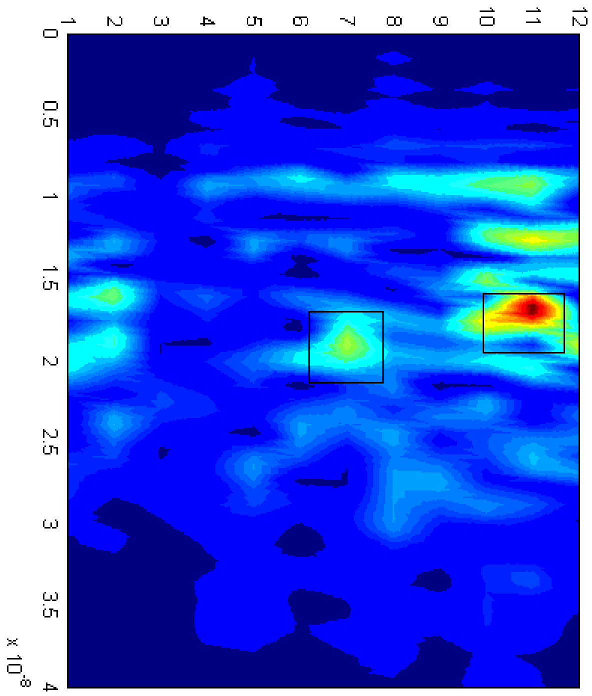

Figure 8: two empty plastic pipes at 85 cm of depth (ungated mode)

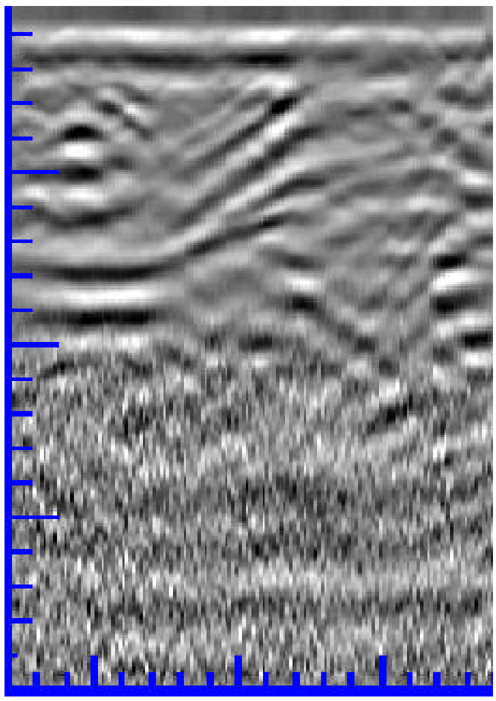

Figure 9: the two same pipes of figure 8 seen with a commercial GPR (courtesy of STRAGO s.r.l.)

As far as deeper targets (more than 120 cm of depth), their returns become difficult to be detected by the radar system. This is due to the strong absorption caused by the humidity of the sand.
In fact, the sand of the pool has resulted quite wet during the whole period of the prospecting (from March until the early days of June): the progressive warming up of the weather has actually dried only the shallower layers (let say 10 cm), but not the deeper levels. So, the relative permittivity has been be estimated about 15 from the return times (which has been verified to be plausible with values found in literature in Daniels D. J., 1996) in addition to the surely present ohmic losses (not quantified). However, the drying of the shallower levels has been seen to decrease the coupling of the antennas, because of the vanishing of ohmic currents in correspondence of the sand areas closest to the antennas. So, the drying of even the shallower layers of sand is not a negligible aspect.
To have an useful term of comparison to support these arguments and to validate the final performances of the realised radar system, a commercial GPR (courtesy of STRAGO s.r.l.) has been also used.
In figure 9 an image of the same two pipes of figure 8 obtained by the impulsive GPR is shown. The scale of the abscissas is evidenced in the lower part of the figure: the distance between two subsequent notches corresponds to 20 cm, both along the abscissa and along the depth. In fact, in figure 9 the return time has been automatically converted into depth by assuming a propagation velocity of 10 cm/ns in the soil. This corresponds to assume a medium relative dielectric permittivity of 9. By re-converting the depth into time, it could be seen that there is a good agreement between the results of the impulsive GPR and the return times registered by our instrument (the re-conversion, of course, has to take into account for the round trip and for the non-zero distance between the transmitting and the receiving antennas). Moreover, it is remarkable the fact that both in figure 8 and in figure 9 the right pipe appears shallower and "stronger" than the other one. However, the image obtained with the stepped frequency GPR seems less affected by artefacts than the other. In particular, 4 subsequent peaks of reflection, likely due to multiple reflections, can be noted in fig. 9 below the left pipe, also accounting for an averaged value.

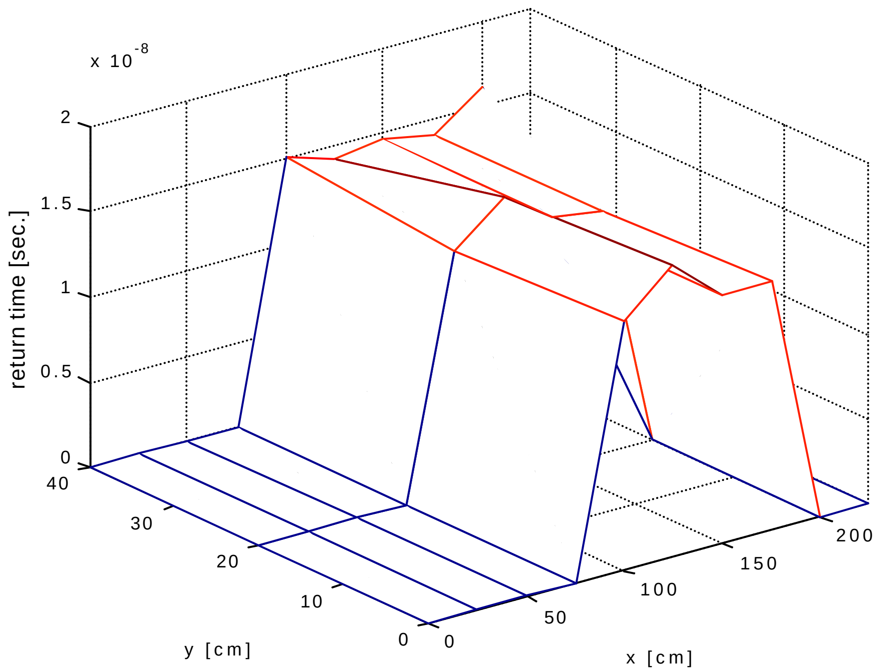

Figure 10: return times of the meaningful radar pulses on the metal sheet at 50 cm of depth (planar scan)

The other comparison tests (not shown here for sake of brevity) confirm that, in the majority of the cases, the qualitative performances of the stepped frequency GPR result better, in the sense that, without any particular processing on the data, the obtained images are clearer and cleaner, in agreement with general well known theoretical previsions (Pipan M., 2000).
Finally, it is worth to show also some comprehensive results of done planar scans. In particular, a common offset planar scan on the same metal sheet of figure 4 is shown in figure 10. This planar scan is composed of 3 B-scans 20 cm spaced, each composed by 10 measurements 25 cm spaced.
More precisely, figure 10 shows a plot of the times of the maxima of the meaningful radar returns for each position of the planar scan. As a criterion to state the meaningfulness of the returned pulse, a threshold of 60% with respect of the amplitude of the more intense returned pulse have been adopted. From figure 10, it is clear that the whole of the meaningful pulses are at about 15 ns and they are precisely localised at one side of the B-scans. Another visualisation can be provided by representing in a colour graph the values of the received pulses after 15 ns for any position of the planar scan, i.e. an image slice at a fixed depth. The result is shown in figure 11, wherein the data have been linearly interpolated, since the available data are only 30, given by the product of the number of B-scans times the observation positions taken for each B-scan. Both in figure 10 and 11 the spaces scales are in cm, whereas the time in figure 10 is in seconds.

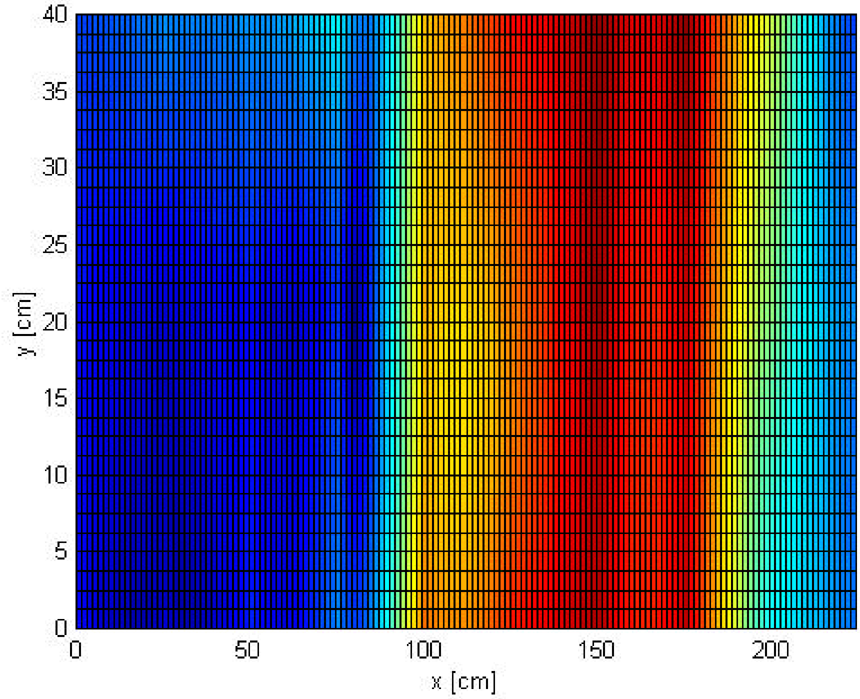

Figure 11: planar horizontal image of the metal sheet at 50 cm of depth corresponding to the return time of 15 ns

4. CONCLUSIONS

Some outdoor experimental tests performed on the stepped frequency GPR system realised in the framework of the project ARCHEO have been exposed. The tests have been done on a dedicated outdoor facility with known buried targets and, therefore, with the aim to validate the system and assess its performances. The description of the potentialities of the radar has been not complete for sake of brevity: let us incidentally outline, for example, that the antennas can be moved also in common depth point, in common receiver and in planar common offset (Daniels D. J., 1996).
Therefore, the system can be very useful to provide multifrequency and multiview data for electromagnetic inversion techniques, which instead is an important aspect of ARCHEO. Moreover, further measurement campaigns to be performed in an actual archaeological site near Capua (Alberti et al., 2000a) are foreseen at the end of ARCHEO project (july 2001). These future campaigns are expected to provide further results and/or suggestions for possible improvements as far as system performances in terms of resolution, dynamics and penetration depth and data processing in terms of target detection and recognition and information presentation to final users.

5. AKNOWLEGMENT

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