Low-Frequency SOUNDER radar system as a new tool for archaeological prospection and monitoring: Potentialities and preliminary surveys

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Abstract. This paper deals with a multimode/multifrequency airborne radar system of relevant interest as a remote sensing tool for archaeological prospections. The system, designed by the Research Consortium CO.RI.S.T.A., works at relatively low frequencies in a band ranging from VHF/UHF to P and L ones. It is capable to operate in two different modes: i) nadir-looking sounder in the VHF band (centre frequency at 163 MHz); ii) side-looking imager (SAR) in the P band with two channels at 450 MHz and 860 MHz. Preliminary flights have been carried out with the aim to validate the performances of the system. Here, we present the outcomes of a preliminary survey carried out over the

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Paestum archaeological site, Southern Italy. The interpretability of the collected data has been enhanced thanks to the use of a microwave tomographic reconstruction approach developed at IREA-CNR. Reconstruction results highlight that the system is capable to provide information at a large scale about the geology of the site and of its shallower layers in a relatively short time.

1. Introduction

Ground Penetrating Radar (GPR) systems mounted on airborne platforms or helicopters represent a significant opportunity for a large scale surface and subsurface prospecting (Machguth *et al.* 2006; Catapano *et al.* 2012). As a matter of fact, unlike their ground-based counterparts, these systems allow fast investigations of wide geographic areas, also hostile or inaccessible, by keeping low the measurement time and high the data collection density. Airborne GPRs have been mainly employed for ice characterization (Machguth *et al.* 2006; Kim *et al.* 2010) due to their subsurface penetration capabilities, but also for river discharge measurement (Melcher *et al.* 2002), oil spill detection (Bradford *et al.* 2010) and localization of avalanche victims (Fruehauf *et al.* 2009). Accordingly, considerable attention has been devoted to the development of airborne radars using low frequency bands ranging from VHF/UHF to P and L ones.

Recently, the Italian Space Agency (ASI) has promoted and funded the development of a new multi-mode and multi-band airborne radar system, which may be considered even a "proof-of-concept" for the next space-borne missions aimed at planetary observations (Papa *et al.* 2012; Catapano *et al.* 2012a). From another perspective, the system can be considered as a validation tool for low frequency radar terrestrial diagnostics, imaging and monitoring applications. The research consortium CO.RI.S.T.A. had in charge of the design, development and flight validation of such a system, which represents the first airborne radar entirely built in Italy.

In this paper, we give a brief description of the designed radar system, which is flexible and capable of operating in two different modes: i) nadir-looking sounder at VHF band (163 MHz); side-looking imager (SAR) at P band with two channels at 450 MHz and 860 MHz. In particular, the focus of the work is to highlight the potentialities of the nadir-looking sounder as a support tool for archaeological prospection and monitoring. As a matter of fact, the sounder offers significant advantages in terms of: ensuring a global vision of the archaeological site and of the embedding territory (by allowing in principle a 3D representation of the site thanks to acquisitions along different flight lines); performing very fast surveys compared to the ones made by ground-based GPR systems; achieving an improved flexibility in the measurement opportunities because it is possible to carry out the survey without interfering with the ordinary activities of the site.

It must be pointed out that the sounder allows to achieve information about deeper zones of the underground; thus, it can be considered as a valuable device in an integrated approach which combines the airborne observations with ground based surveys (e.g. based on GPR, electrical resistivity tomography, electromagnetic induction).

Here, as a preliminary proof of the effectiveness of the system, we show the outcomes of a survey performed at the archaeological area of Paestum, which is, as well known, a site of very high cultural-historical significance. In this case, the sounder system turns out to be useful to retrieve information about the "geology" of the site and of its shallower layers. The interpretation of the collected data is enhanced by a suitable microwave tomographic approach developed at IREA-CNR (Papa *et al.* 2012; Catapano *et al.* 2012a), which is capable to provide images of selected surveyed areas with enhanced spatial resolution.

2. Description of the radar system

The system exploits three different frequency bands and has both subsurface and SAR imaging capabilities. The sounder operates with a carrier frequency of 163 MHz and an effective bandwidth of about 10 MHz. As regards the SAR working modality, two frequency ranges are used to achieve lower and higher resolutions, respectively. The lower resolution SAR (SAR-Low) imager operates at 450 MHz with a 40 MHz bandwidth, whereas the higher resolution SAR (SAR-High) imager operates at 860 MHz with a bandwidth of 80 MHz. for both the modes (sounder and imager), a linear frequency modulated signal is transmitted, where the bandwidth is synthesized in the imager mode by a stepped chirp and each bandwidth step is 10 MHz.

The entire system is composed by three main blocks: the Radar Digital Unit (RDU), the Radio Frequency Unit (RFU) and the Power Supply Unit (PSU). The RDU has in charge the parameters setting, timing generation and data handling

Fig. 1 - Photo of the sounder and imager antennas installed on the civil helicopter.

The RDU is a full programmable digital unit comprising the Analog to Digital Converter (ADC) and data storage unit. The RFU embeds the Frequency Generation Unit (FGU), which has the task to generate all synchronisms and RF signals, the DSP that generates the Low Frequency Modulated (LFM) signal chirp by means of digital synthesis technique. The PSU provides power supply to all the system that is powered by means of external 28 V DC voltage.

The system design is conceived in such a way that most part of the building blocks are shared by sounder and imager functionalities. In particular, the base band signal generation, base band data sampling and data handling are common to both sounder and imager operational mode. This represents the main feature of the entire system. The great advantage lies in the use of the same ADC, which has been possible by the usage of under sampling technique.

Three different antennas have been adopted: one for the sounder and two for the imager modalities. The sounder antenna is a log periodic one with four radiating elements. The imager antennas are planar array designed and realized by University of Calabria (Cosenza, Italy). A photograph of the sounder and imager antennas installed on the civil helicopter used for the surveys is shown in Figure 1.

Platform altitude and geo-referencing are ensured by external GPS/INS linked by serial port to the RDU. The nominal performances of the system in the two operation modalities are summarized in Table 1.

Both data from sounder and imager can be processed by an ad-hoc configurable software (SW). For the results presented in this work, the basic range compression and the Hanning sidelobe suppression functions are adopted as pre-processing tools of the acquired sounder data. Hence, a model-based tomographic reconstruction technique is applied.

Table 1 - Nominal performances of the system

	Sounder	SAR Low	SAR High
Across Track resolution			
Range resolution (free space	15 m	3.75 m (stepped)	1.87 m (stepped)
Along track resolution	27-280 m @3000m.	4.8 m @ 4 looks	2.5 m @ 2 looks
Penetration Depth	100 m (moderate attenuation ter-rain)		

3. Tomographic approach

A tomographic approach belonging to the class of the linearized inverse scattering techniques based on the Born approximation, has been recently proposed in (Catapano *et al.* 2012a, 2012b) with the aim to improve the focusing of the radargram acquired by airborne GPRs. The approach was based on a ray model to simplify the evaluation of the incident field and the Green's function involved in the scattering operator. The resulting linear inverse problem was solved by using the Singular Value Decomposition (SVD) (Bertero & Boccacci 1998)

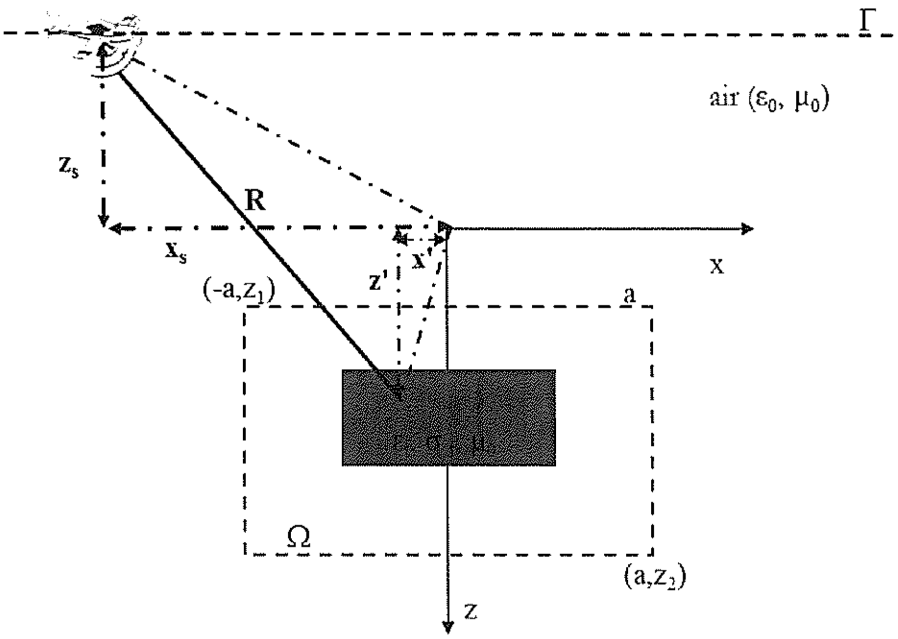

Fig. 2 - Sketch of the reference scenario for the microwave tomographic approach.

Here, we simplify the model compared to the one in (Catapano *et al.* 2012a) by assuming the free-space as background scenario instead of a half-space configuration. This assumption is reasonable since the sounder could be used to detect and characterize surface objects. Moreover, the propagation in the ground is much less significant than that in free-space, thus the distortion effects due to an inaccurate model of the actual wave propagation path can be considered negligible.

With reference to the 2-D geometry sketched in Fig. 2, the objects are assumed invariant along the direction perpendicular to the (*x*, *z*) plane. The transmitting and receiving antennas move along a linear trajectory Γ at fixed distance from upper edge of the investigated domain

$\Omega \in [-a,a] \times [z_1, z_2]$. A transverse magnetic (TM) polarization is assumed where the incident electric field is directed along the *y*-axis. A multi-monostatic/multi-frequency measurement configuration is considered, i.e. the transmitting and receiving antennas are located at the same point (x_S, z_S) and radiate in the frequency interval $f \in [f_{\min}, f_{\max}]$. The integral relation to be inverted is given by

$$E_S(x_S, z_S, f) = C \int_{-a}^{a} \int_{z_1}^{z_1} \frac{\exp(-j2\beta_0 R)}{R} \chi(x', z') dx' dz' \tag{1}$$

In eq. (1), $E_S(x_S, z_S, f)$ is the field backscattered at the point (x_S, z_S) at the frequency *f*, $R = \sqrt{(x_S - x')^2 + (z_S - z')^2}$ is the distance from the antenna to the point (x', z') in Ω, β_0 is the wave-number in free space, *C* is a function accounting for all the quantities not involved directly in integral equation, and $\chi(\cdot)$ is the contrast function defined as

$$\chi(x', z') = \frac{\varepsilon_{eqT}(x', z') - \varepsilon_0}{\varepsilon_0} \tag{2}$$

ε_{eqT} being the equivalent permittivity of the target and ε_0 the di-electric permittivity of the free space.

After a discretization of the problem, a matrix relationship is achieved between the scattered field data and the contrast $\chi(\cdot)$; a truncated SVD (TSVD) is adopted as regularization tool for the inversion in order to find a stable solution (Catapano *et al.* 2012b).

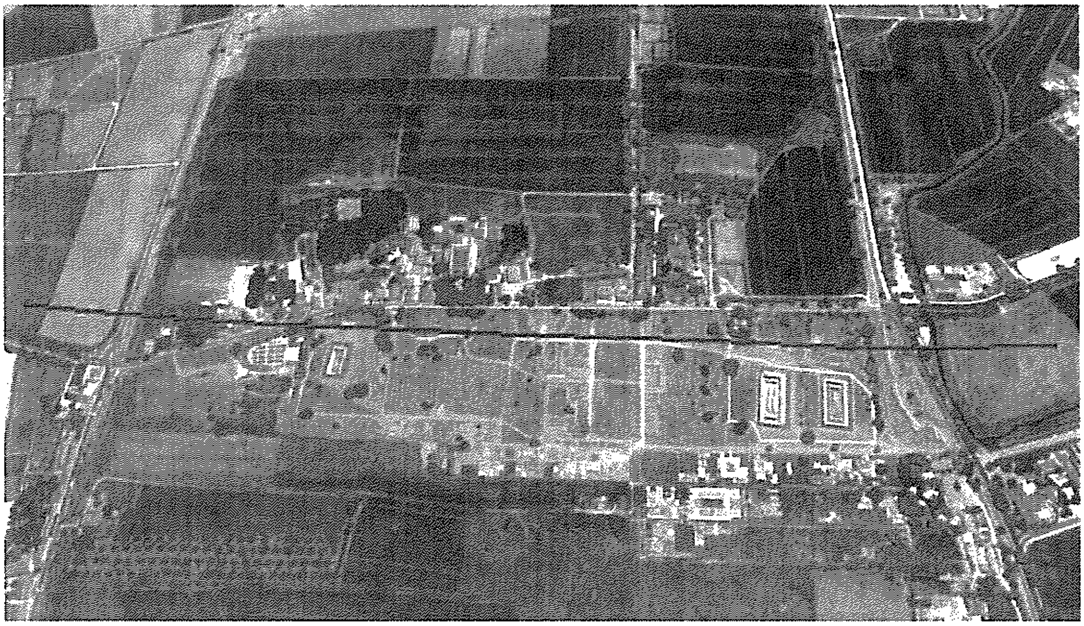

Fig. 3 - Aerial view of the sounded region (flight trajectory in red line).

4. Experimental results

This Section is devoted to present some outcomes of the survey carried out at the Paestum archeological site. An aerial view of the surveyed zone is shown in Figure 3 and the corresponding time-space radargram (B-scan) is displayed in Figure 4.a. The data were acquired over a path about 1200 m long at a mean altitude of 1320 m and with an average flight velocity of 37.55 m/s. Note that the image (see fig. 4.a) has been saturated in order to point out the signals backscattered from the deeper zones, which are obviously weaker than that related to the air-soil interface. As can be seen, the subsurface scenario is rather complex, but interestingly some buried interfaces appear at an equivalent depth (by assuming the electromagnetic velocity in free-space) ranging from 140 m to 200 m; these interfaces are particularly evident in the interval [550, 700] m along the flight direction (i.e. x-axis). In absence of the information of the dielectric permittivity of the soil, it is not possible to provide an accurate information about the actual depth of the targets; in general, this entails the necessity to gain the information about the dielectric permittivity from previous studies/surveys and/or by ground measurements.

In order to improve the image of the subsurface scenario, the tomographic reconstruction has been performed by using the technique described in the previous section. In particular, to reduce the computational burden, the radargram collected by the sounder has been partitioned in 8 subsets (150 m wide) with a spatial step of 0.94 m between adjacent traces. For each subset, the zero of the temporal axis has been set in correspondence of the interface air/ground and a time gating has been applied to remove the air-soil reflection. Then, the data have been transformed into the frequency domain, and the effective bandwidth of 10 MHz with a spacing of 0.4 MHz has been considered for the inversion stage.

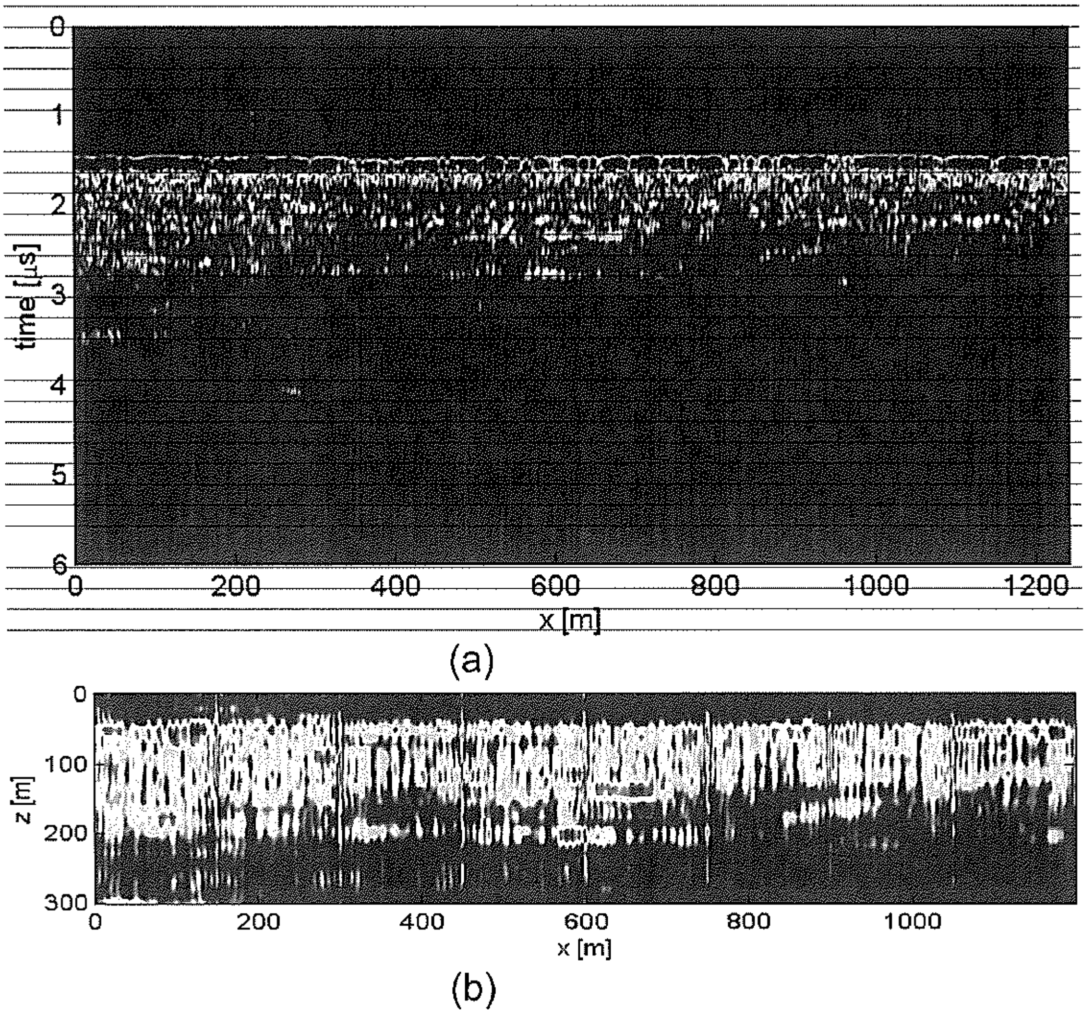

Fig. 4 - (a) Measured radargram. (b) Tomographic reconstruction: the zero of this image corresponds to the air/soil interface, which was erased by a time-gating procedure.

The tomographic image is displayed in Figure 4.b; as can be seen, it clearly highlights the presence in the whole surveyed region of two parallel and flat interfaces at equivalent free-space depths of 50 m and 100 m, respectively. Moreover a third deeper interface appears at a free-space depth of about 200 m, this interface is flat up to x = 800m and then it goes up with a slope of 30°-40°.

5. Conclusions

This work has presented a low frequency multifunctional radar designed to operate in sounder and imager modality. The proposed system, promoted by ASI and realized by CO.RI.S.T.A., has been validated on flight in the sounder mode and the measurement data have been processed by a model-based microwave tomographic approach developed at IREA-CNR. Preliminary results acquired over an archaeological site have confirmed that the system propely works and constitutes a useful tool for getting geological information over large scale in relatively short times.

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