Advanced stepped frequency GPR development

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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 (M.U.R.S.T.), 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 meet archaeological requirements and it will be used to identify and characterize buried finds.

The system is a stepped-frequency radar, capable of transmitting up to 800 MHz in the 100-900 MHz frequency range. The receiving chain has been designed to assure a very low level of phase and thermal noise in order to get a high final value of signal to noise ratio necessary to obtain very precise phase measurements even in presence of weak return signal. The radar is able both to work in continuous and in gated modes to suppress the effects of antenna leakage and strong signals of shallow reflectors.

An advanced A/D converter acquires the received signal with about 17 effective bits, while a computer by means of software developed under LabView controls the whole system. Two log-spiral antennas are used and a maximum power of 10 W is provided to the antenna.

Finally, the system is equipped with an automated positioning system that allows moving the transmitting and receiving antennas independently in a 3-D space. The positioning mechanism has been designed to speed up the measurement survey and to obtain the necessary location precision and repeatability required by inverse imaging algorithms.

The paper summarizes the main guidelines followed during the design phase and presents the radar architecture.

Keywords: Stepped frequency radar, GPR system, Archaeology.

1. INTRODUCTION

The ability of electromagnetic waves to propagate beyond the physical discontinuities that there are between different media makes it possible to exploit them to investigate internal features of dielectric bodies. This property has arisen an endless number of practical applications, ranging from medical prospecting to detection of mines or nondestructive testing of industrial items[1]. In this paper we are concerned with archaeological prospecting by making use of a GPR[2]. In particular, we describe a new system realized by the CO.RI.S.T.A. within the project ARCHEO, funded by the Italian M.U.R.S.T.. This three years programme is aimed to develop advanced devices and techniques to be used for detection and recovery of archaeological zones[3]. In particular ARCHEO is subdivided in three main lines of activity, devoted to the development of a) GPR systems for locating and characterizing archaeological sites and finds, b) a Mobile Unit equipped with hardware and software tools for data acquisition and recording before, during and after excavations, c) a knowledge-based system to assist design, execution, and maintenance of excavations in difficult conditions (e.g. urban areas).

The activities of ARCHEO have been started with the specification of the requirements of the system to be realized. This has been done by a committee of archaeologists, that have pointed out their needs about the system and the purposes it pursues. Therefore it has established that the radiation have to penetrate the soil until the depth of about three meters, with a vertical resolution of 15 centimeters and a horizontal resolution of 50 centimeters. The targets of interest are walls, floors, foundations, wells, ovens, temples, graves, roads and waterworks.

At the same time, it has been conducted an investigation on the various kinds of nondestructive techniques available, and it has been found that GPR technique was the most suitable for the purposes of ARCHEO. Comparisons have been carried out with seismic methods, inductive electromagnetic methods, magnetic methods, resistive methods and methods based on gravity strength[4]. In particular, the choice of a stepped frequency (SF)[2] system has been adopted, because (as it has been known since the early seventies[5]) the SF systems show several technological advantages with respect to the traditional

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impulsive GPR systems, spacing from the larger dynamic range to greater signal to noise ratio attainable due to the narrow band of the system about each of the exploited frequencies[6]. In particular, we want to outline the fact that an SF system allows to relax the band requirements on the ADC converter adopted, because it needs a much lower sampling ratio than that required by an impulsive system. We will develop in more depth this point in the section on the hardware of the system. A quite innovative aspect of the project ARCHEO is that GPR data will be elaborate by an inverse scattering[7] technique rather than to perform the classical detection of echoes to synthetic pulses. Actually, inverse scattering techniques for retrieving buried objects are a well known subject[8-10], and retrieving of test objects by these technique has been already successfully performed (i.e. in ref. 10, but not only), however, at our knowledge, this is the first time that an inverse scattering technique is experimented in such a large scale. The inversion algorithm has been set up by the electromagnetic departments of the two Universities "Federico II" and "Seconda Università degli Studi di Napoli". It is worth noting that the inversion is foreseen to be performed by a linear algorithm dealing with data in the frequency domain, as it has been done in plenty previous works[8-10]. Also for this reason, the use of SF system seems particularly favorable, because it allows to gather data in frequency domain, without needing to Fourier-transform the time domain data provided by an impulsive GPR. A further innovation in the inversion scheme is that measurements will be taken within a multiview multistatic[8-10] and multifrequency configuration rather than the classical multimonostatic scheme adopted in GPR prospection[2,5-6,10-11]. This makes necessary to design a positioning system that allows to change the location of the antennas in an independent 3-D and controlled way. The positioning system is therefore an important part of the overall system and the necessary attention has been devoted to its design: it will be described in the section dedicated to the hardware of the system.

Moreover, a gated mode[11] has been added to the traditional ungated one in order to avoid the leakage between the transmitting and receiving antennas[2], that is a relevant problem above all for SF systems working only in continuous mode[2,6]. The choice of a gated system compels to adopt a subsurface region of investigation that does not start with the air-soil interface, but this is not a severe limitation for archaeological application, since most of the finds of interest are located deeper than about 50 cm. The adopted antennas are wide band spiral ones and their characterization is being performed by the University of Cosenza (Italy) both by experimental measurements and by computer simulation by means of the commercial software High Frequency Structure Simulator (HFSS), that is an Ansoft's product. It is worth noting that the electromagnetic simulations are being performed in presence of the air-soil interface, because it influences meaningfully the radiated field and the input impedance of the antennas throughout the whole frequency range adopted. Let us outline that the characterization of the antennas is particularly needed by the inverse scattering algorithms, because the linear method implemented requires the knowledge of the field incident in the soil in absence of any scattering object.

2. HARDWARE OF THE SYSTEM

In this section we show a detailed block diagram of the developed SF GPR. The scheme to which we refer is depicted in fig. 1 and, the main system parameters are shown in table 1. The main body of the system includes two synthesizers operating over the frequency range 10 KHz - 1 GHz with a minimum resolution of 0.2 Hz. The output power level is comprised between -137 dBm and 13 dBm with a resolution of 0.1 dB. The switching time is 15 μs in the worst case and each synthesizer can operate in high-speed digital sweep with a maximum number of 8192 steps, each of which can be set from 10 μs up to 10 s.

To reduce the effects of flicker noise[12] at low frequency, the Tx and Rx synthesizers generate RF tones with a "spectral distance" of 1 MHz in ungated mode and of 101 MHz in gated mode. In both cases, the intermediate frequency (IF) signal is 1MHz and a 100 MHz coherent oscillator (COHO) oscillator is required along the receiving gated chain.

The digital attenuator along the transmitting chain allows an amplitude modulation to compensate the variable attenuation introduced by the system in the band of interest and to shape the synthetic pulse in the frequency domain as needed. Let us outline that this possibility of easily modifying the transmitted signal is another remarkable advantage of the SF systems with regards to the impulsive systems[2,5-6,12].

The power amplifier provides a high power signal (up to about 10 W) to the antenna feed point.

The antennas consist of two-arm log-spiral radiating elements. These antennas have been chosen because of their broad band and their single lobe pattern. In fact, due to the inversion scheme adopted, it is expected not convenient a radiation pattern with several nulls. They are constructed with a layer of radome between the spiral and the air-soil interface that protects the radiating element by soil pieces of asperity (see figure 2). The radiating elements are mounted on a dielectric support and the whole radiating system is shielded by a metallic box to isolate it against environmental interference. Finally, a thick layer of graphite is placed at the back of the antenna in order to absorb the electromagnetic power radiated towards the shield. Table 2 lists electromagnetic characteristics of the materials above and table 3 reports their thickness.

Log-spiral antennas are circularly polarized along the z-axis[13] (see fig. 3), and in order to detect a wider class of targets, our GPR system can be easily configured to work with two antennas with either the same or opposite polarization.

University of Cosenza performed the antenna characterization by experimental measurements and software simulations. The experimental measurement has been conducted in free space by measuring the input impedance and the reflection coefficient in the frequency band 40-1000 MHz with a network analyzer. Instead, the simulations have analyzed the antenna behavior both in free space and in presence of the air-soil interface. The first simulation results show a good agreement with those obtained by network analyzer. The electric field has been computed on a plane near to the transmitting antenna and parallel to it. The plane is wide enough to consider negligible the field outside it and the sample spacing has been chosen on the basis of the Nyquist theorem. In such a way, the electric incident field can be calculated everywhere in terrain by its plane wave spectrum. Let us recall that this calculation is important for the inversion algorithm, as stated before.

Table 1. Main characteristics of the system

Depth of penetration	3 m
Horizontal resolution	50 cm
Vertical resolution	15 cm
Frequency range of the radiated waves	100-900 MHz
Frequency range of the synthesizers	10kHz-1 GHz
Frequency resolution of the synthesizers	0.2 Hz
Range of the output power level of the synthesizers	From -137 dBm up to 13 dBm
Power level resolution of the synthesizers	0.1 dB
Maximum switching time of the synthesizers	15 μs
Maximum number of steps of the synthesizers	8192
Length of a single step	From 10 μs up to 10 s
Intermediate frequency for both gated and ungated modes	1 MHz
COHO frequency for the gated mode	100 MHz
Resolution of the ADC	23 bit
Dynamic range of the ADC	More than 100 dB
Maximum sapling ratio of the ADC	20 MHz
Power at the antenna feed point	Up to 10 W
Band of the filter R1	2 MHz
Band of the filter R2	25 kHz
Band of the Filter S1	12 MHz
Band of the Filter S2	140 kHz
Size of the positioning system	320x320x100 cm^3
Resolution of the positioning system	1 cm

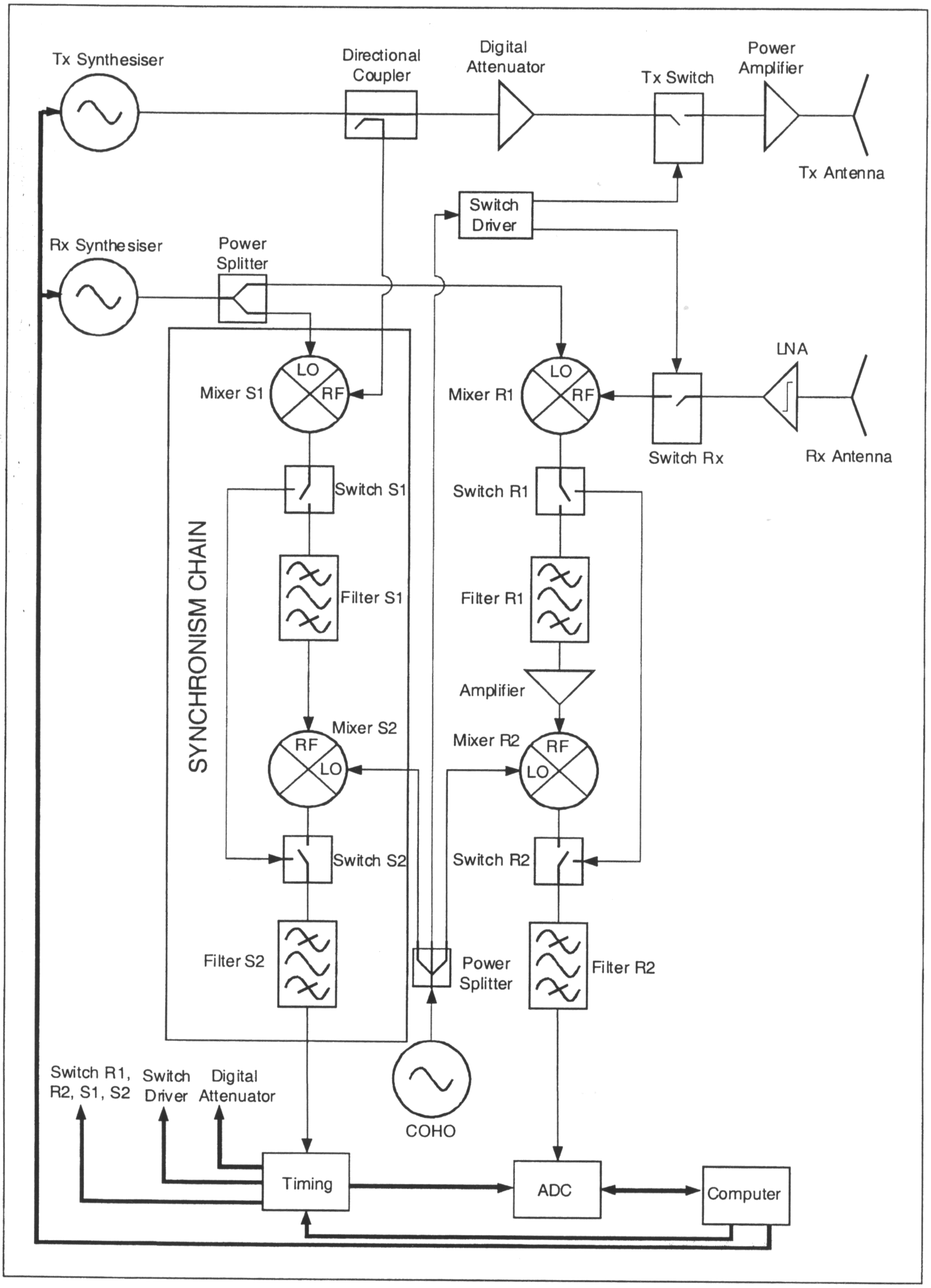

Fig. 1. Block diagram of the CO.RI.S.T.A. Stepped-Frequency GPR

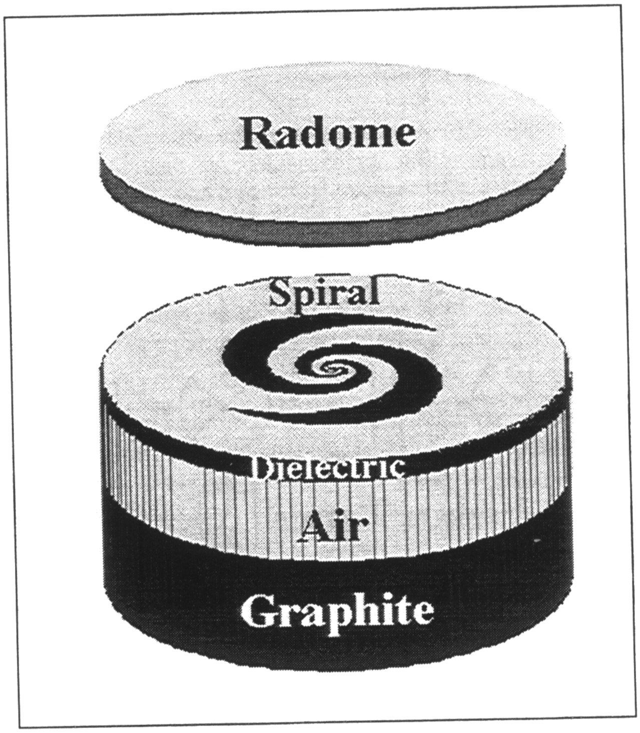

Fig. 2. GPR antenna

Table 2. Electromagnetic characteristics of the materials

Materials	ε_r	σ (S/m)	Tan(δ)
Radome	2.6	0	0.01
Dielectric	3	0	0.0012
Graphite	1	7×10^4	0

Table 3. Thickness of materials

Materials	Thickness (mm)
Radome	25
Dielectric	1.5
Air	67.5
Graphite	56

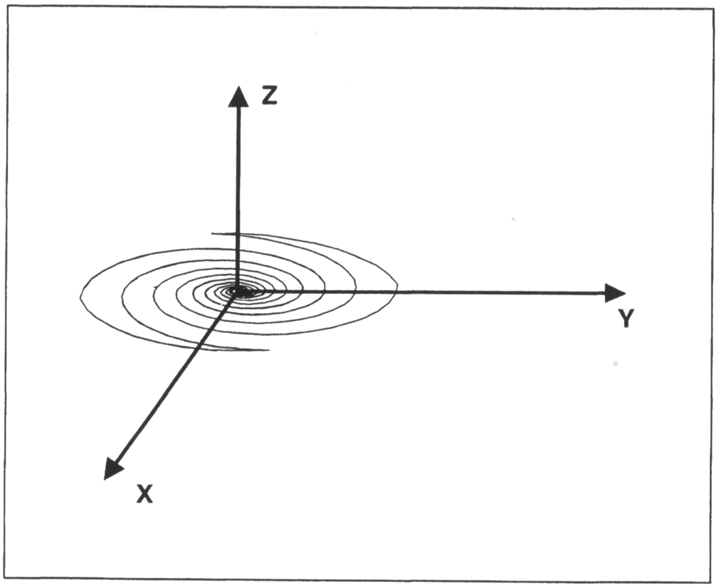

Fig. 3. Antenna reference frame (axis z is to be meant towards the direction of the depth in the soil)

Fig. 4 shows the modulus of the x component (the reference system is that of fig. 3) of the electric field computed at 500 MHz on a plane parallel to the air-soil interface, at the depth of 36 mm, sized 600×600 mm in a terrain with $\varepsilon_r = 4.46$ and $\sigma = 2.32$ mS/m.

The received signal is amplified by a low noise amplifier and then down-converted by the mixer R1 (see fig. 1). If the GPR works in ungated mode, the down-converted signal is beated at intermediate frequency and the filter R2 eliminates the signal component at frequency sum. The bandwidth of this filter is about 25 KHz to reduce as much as possible the thermal noise in input to the ADC.

Part of the transmitted signal is coupled to the synchronism chain in order to generate the ADC external clock, that is obtained by means of a multiplication by a factor 3 of the 1 MHz signal at the output of S2 filter. The frequency multiplication is performed by harmonic distortion and filtering within the Timing block of fig. 1.

It is worth noting that, after the calibration procedure (that compensates the different electric paths of the signals), the phase difference between the received and synchronism tones depends only on the path covered by the transmitted signal into the terrain. In fact, the GPR has been designed so that each random phase shift be present both on the received and synchronism signals.

The HP E1437A ADC, an exceptionally low distortion digitizer, performs the sampling. The device resolution is 23 bits and its maximum sample rate is 20 MHz. The internal anti-aliasing filter is flat up to 8 MHz and rejects signal above 12 MHz with an attenuation of at least 100 dB. The converter also demodulates the signal providing the in-phase and in-quadrature components. The ADC uses digital circuitry (DSP) to allow programmable changes of the center frequency and signal bandwidth and this is done at high speed for real-time operation by means of zoom and decimation filtering. In such a way it is possible to obtain at least 17 equivalent bits, namely a dynamic range greater than 100 dB.

As already prompted, the developed GPR foresees the possibility of working in gated mode to overcome the main disadvantage of ungated systems, i.e. the received strong signal due to either the leakage between the transmitting and receiving antennas or to shallow strong reflectors that can mask weaker signal from deeper targets. In such a system, the stepped-frequency is pulsed and a "gate" in reception allows to pass signals reflected from the desired depths whereas unwanted reflections are rejected.

The transmitted and received signals are gated "on" and "off" by means of fast GaAs FET switches driven by an Altera's gate array. The minimum length and the repetition time of the pulses depend on the frequency of COHO that drives the Tx and Rx switches (see fig. 1). In our case the minimum length is 10 ns and both the pulse length and the repetition time have to be an integer multiple of this value. The gate array allows to set all duty cycles that match the constraints mentioned above.

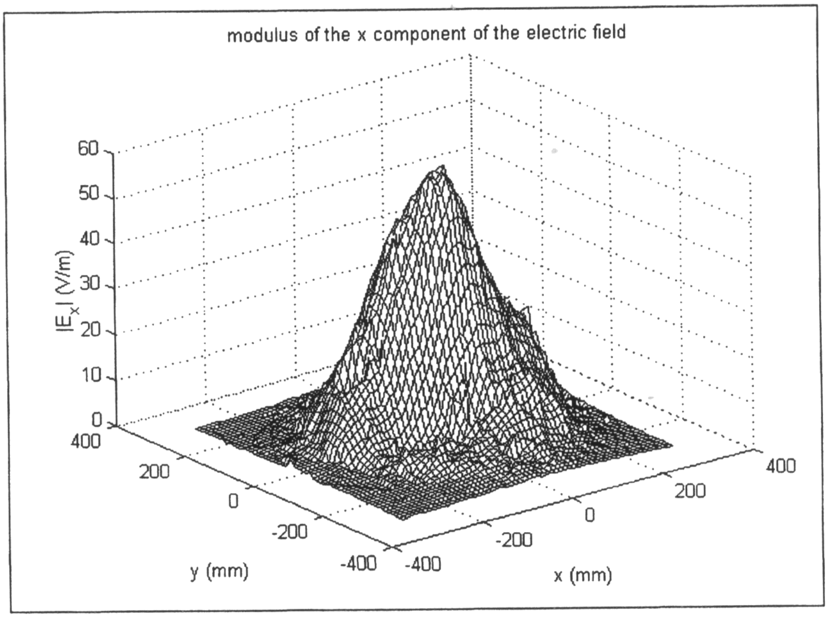

Fig. 4. Modulus of the x component of the electric field

The received gated signal needs two down conversions. After the first beat, the signal is centered at 101 MHz and its bandwidth is 100 MHz at most. A second filtering is then performed to reject the frequency sum and above all to reduce the aliasing introduced by the second down-conversion. This filter (R1 in fig. 1) has been designed and realized with a bandwidth of about 2 MHz. As mentioned above, the signal at 101 MHz is then down-converted at intermediate frequency by using the 100 MHz COHO oscillator.

Finally, let us specify some important features of the positioning system. First of all, in order to perform a multiview inversion scheme the positions of the antennas have to be known with a precision much smaller than the minimum wavelength (we refer to the wavelength in air) adopted. The positioning system projected will allow a precision of the order of one centimeter, that is enough because the maximum frequency adopted is 900 MHz. It will have a size of 320x320 cm and a highness of 1 meter, but it will be also reducible in case of particular conditions during the measurement campaign. Its main structure is similar to those of a mobile bridge with two sliding points (see fig. 5). Its sliding trolleys are driven by stepper motors and, wherever possible, plastic materials have been preferred in order to avoid any possible unwanted electromagnetic interference. For the same reason, the driver of the motors has been appositely designed such as it suspend the generation of all the non-continuous currents during any period of radio-waves acquisition.

3. SOFTWARE OF THE SYSTEM

The general scheme of the software of the system is shown in fig. 6. Essentially, it consists of three distinct parts: input parameters setting, programming of GPR subsystems and scanning and post-processing of the acquired data. The most important of the three parts is the input parameter setting.

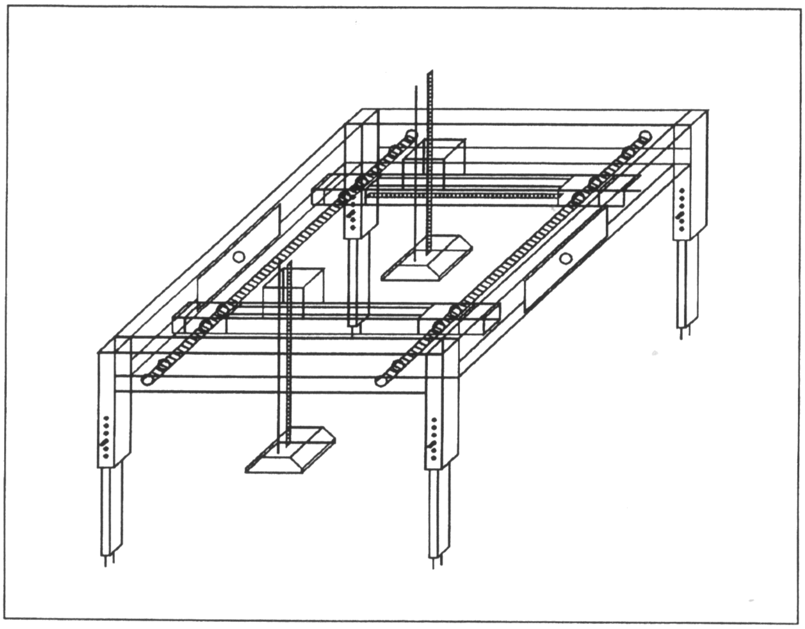

Fig. 5. Positioning system

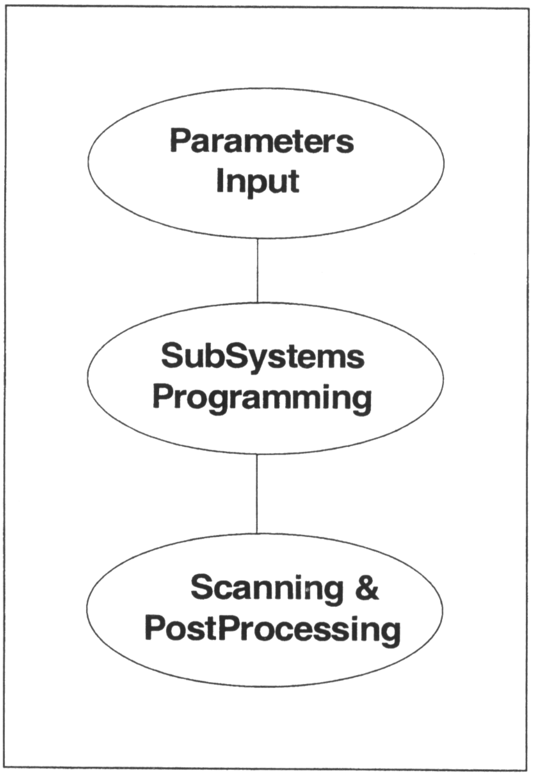

Fig. 6. General scheme of the software of the system

The input parameters setting has been structured into two basic parts: general parameter input, which allows to define the area to scan and to set the different parameters that define the scanning modality[2] and hardware parameter input which allows to define all standard parameters that usually define a SF system[6,11-12] as well as the timing of the subsystems. Both input settings have been realized by means of visual interfaces to facilitate the users.

The programming language chosen to realize the software is LabView by National Instruments, because it is one of the most used language in automated test equipment (ATE) facilities and because it shows the attractive feature to realize friendly Man-Machine Interfaces. Moreover, LabView allows to realize, easier and faster than other languages, both the development and the testing of prototypes and the implementation of communication links among the different GPR subsystems according to the different protocols used (i.e. IEEE 488, RS-232, VXI backplane).

4. CONCLUSIONS

In this paper the GPR system developed within the project ARCHEO (still "in fieri") has been presented. Currently, the hardware and the software of the system have been already realized, and the first laboratory tests on the system are being performed. Moreover, the antennas singularly considered have been characterized in presence of the air-soil interface. The characterization of the behavior of two antennas in presence of each other is foreseen by next months, even if, due to the pattern of the antennas joined with the unavoidable losses of the soil, only a low coupling effects is expected. Next step will consist in the instrument validation by means of measurements campaigns. These activities will be organized in two subsequent steps, which reflects two validation goals. The first step will be aimed to calibrate the whole system in a controlled environment with known targets. To this end, a specific test-site, composed by a rectangular tank filled of sand of river and/or clay, with size 25x25 meters, and deep 4 meters, has been built up. During the second step the GPR will be tested in actual archaeological sites with unknown targets. In particular, together with the archaeologist committee, the two sites of Cales and Sinuessa, that are two ancient Roman towns in Campania (Southern Italy), have been selected.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

1. J. Ch. Bolomey and Ch. Pichot, " Some applications of diffraction tomography to electromagnetics-the particular case of microwaves", in Inverse Problems in Scattering and Imaging, M. Bertero and E. R. Pike, eds. (Higler, London, 1992), pp. 319-344.
2. D. J. Daniels, Surface-penetrating radar, The Institution of Electrical Engineers (London, 1996).
3. Contratto di Ricerca 179201-1325/458, Ministero dell'Università e della Ricerca Scientifica e Tecnologica, Roma, Italy, 1996.
4. S. Esposito, M. Bortone, "Tecniche e sensori per lo studio del sottosuolo", technical report A11-COR/NT/002,available (in Italian) upon request at CO.RI.S.T.A.
5. L. Robinson, W. B. Weirand L. Yung, " Location and Recognition of Discontinuities in Dielectric Media Using Synthetic RF Pulses", Proc. IEEE, vol. 62, N. 1, pp. 36-44, Jan. 1974.
6. D. A. Noon, Stepped-Frequency Radar Design and Signal Processing Enhances Ground Penetrating Radar Performance, Ph.D. Thesis, Department of Electrical & Computer Engineering, University of Queensland, Australia, 1996.
7. D. Colton and R. Kress, Inverse Acoustic and Electromagnetic Scattering Theory, Springer-Verlag, Berlin, 1992.
8. D. Lesselier and B. Duchene, "Wavefield inversion of objects in stratified environments: from back-propagation schemes to full solutions", in Review of Radio Science 1993-1996, ed. R. Stone, Oxford Univeristy Press, 1996.
9. R. Pierri, G. Leone, R. Bernini and R: Persico, "Tomografic inversion algorithms for permittivity reconstruction in subsurface prospection" in Proc. of 7th Int. Conf. On Ground-Penetrating Radar, Lawerence, USA, 1998.
10. T. B. Hansen and P. M. Johansen, "Inversion scheme for ground penetrating radar that takes into account the planar air soil interface", IEEE trans. on geoscience and remote sensing, vol. 38, N. 1, pp. 496-506, Jan. 2000.
11. G.F. Stickley, D.A: Noon, M. Cherniakov, I.D. Longstaff, "Gated stepped-frequency ground penetrating radar" Journal of Applied Geophysics, vol. 43 (2000), pp. 259-269, 1999.
12. S.K. Koppenjan, C.M. Allen, D. Gardner, H.R. Wong, H. Lee, S.J. Lockwood, "Multi-frequency synthetic-aperture imaging with a lightweigth ground penetrating radar system" Journal of Applied Geophysics, vol. 43, (2000), pp. 252-258, 1999.
13. Nakano, K.Hirose, I.Ohshima and J.Yamauchi, "An Integral Equation and its Application to Spiral Antennas on Semi-Infinite Dielectric Materials", IEEE trans. On Antennas and Propagation, vol. 46, N. 2, Feb. 1998.