Experimental tests for characterization of GPR antenna patterns

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Abstract
Detection and location of buried structures using the electromagnetic impulsive methodologies (GPR) require the study of the spatial distribution of energy irradiated by an antenna into the ground and the mechanisms of wave propagation and scattering from relevant targets. Evaluation of the difference in wave field distribution in the ground with respect to free space can provide some useful indications on the propagation of the Georadar signal in the ground and the spatial resolution capability of the GPR method. For this reason, a research group, involving «La Sapienza» University, Rome and the National Research Council began, during 1992, to perform studies on antenna radiation pattern, the propagation and scattering phenomena of GPR. This paper presents the experimental set up and the obtained results on the antenna radiation pattern.

Key words *georadar – radiation pattern – antenna*

1. Introduction

Ground Probing Radar is a geophysical detection method based on the use of electromagnetic pulses, which is orientated towards exploring the subsoil. GPR has numerous applications including: mineral detection, determining bedrock or water table depth, archaeological research, detecting technical networks such as cables, pipes, tunnels and detecting faults in rocky formations.

The electromagnetic pulses sent into the ground by the GPR antenna propagates at a velocity which depends on the electrical characteristics of the medium (Fenner, 1992). The wave equation (Olhoeft, 1985) regulates the propagation conditions of the electromagnetic field in the medium. The solution to this equation can prove to be complex, especially if we consider that the spatial distribution of the radiated energy and the parameters of the antennas employed, undergo modifications due to the presence of the air-ground interface (Collin, 1985; Engheta *et al.*, 1982; Arcone and Delaney, 1981; Smith, 1984).

Thus, it is important to know the radiation and directivity diagrams in free space to understand the coupling phenomenon between the transmitting and the receiving antennas (when bistatic) as well as between the antenna and the ground. This information can be useful for evaluating the variations of spatial distribution of the radiation inside an electromagnetically complex medium such as the ground.

Since information concerning this type of instrumenation is not available on the market at the moment, a series of experiments were conceived and carried out in 1992. These experiments were specifically aimed at determining the radiation patterns of Georadar antennas as well as studying and analysing the pulse waveform received.

It is well-known that the radiation pattern from an antenna is usually measured in an anechoic chamber, that is to say, a monitored ambience, especially set up to cancel the phenomenon of pulse reflection coming from objects outside the antennas. The measurements are carried out by moving an object of known dimensions (probe) in a prefixed direction, relative to the transmitting antenna placed in a fixed position. This technique permits the reconstruction of the radiation pattern on the planes containing the electrical component ***E*** and the magnetic component ***H*** of the electromagnetic field.

In the case of a bistatic radar, it is possible to reconstruct the radiation pattern of both antennas by moving one in relation to the other, along prefixed planes and recording the pulse received in each position.

2. Evaluation of radiation patterns

The experimental measurements for determining radiation patterns were carried out in free space using the Georadar OYO YL, R2 (mod. 2419A) equipped with two dipolar antennas (bow-tie; mod. 2427 U.K. OYO) at 600 MHz rated frequency and an approximative dipole length of $\lambda/2 = 0.25$ m.

The radiation patterns were measured on two planes, perpendicular to each other. Figure 1a-c illustrates the type of antenna used and the two planes *XZ* and *YZ* parallel to field ***H*** (plane ***H***) and to field ***E*** (plane ***E***), respectively.

The measurements were carried out in free space, that is to say, in a medium ($\varepsilon \equiv \varepsilon_0$) which, at the frequencies used is assumed to be continuous, homogeneous and devoid of loss.

3. Experimental configuration and data collection

When arranging the experimental configurations, the following aspects were taken into account: a) the distance that separates the receiving and transmitting antennas; b) the possibility of changing the position of both antennas; c) the absence of external reflection sources which could interfere with direct signals between the antennas.

Bearing in mind these aspects, the two irradiated systems were placed at a reciprocal distance of 4 m. Moreover, to make sure that the reflex pulse from the ground did not interfere with the direct one between the antennas, they were placed at a height of 4 m. Considering in fact, a nominal duration of 3 ns of the pulse in air, this height guarantees that the radiation reflected from the ground surface reaches the receiver at least four times later than the direct pulse.

The support structures of the radiating system were constructed using four wooden posts, 15 cm in a diameter, fitted into the ground and kept in a vertical position by rods (fig. 2). Furthermore, in order to carry out the measurements on the two planes of fig. 1, two PVC rotating supports were used, which had two rotating axes placed at a distance of 180° from each other and capable of rotating at 360°.

After a series of calibration tests on the instruments, the following instrumental configuration was adopted: amplification: 12 dB (Probe gain); TVG: off; Gain control: fix; time scale: 25 ns; band pass filters: 10 Hz (HPF) – 1600 Hz (LPF); stack 16; scan rate: 100 ms. This set up permitted us to obtain the direct pulse in free space, so preventing amplitude saturation phenomena.

Before starting to measure the patterns, the dipoles of the two antennas were changed over in order to verify their reciprocity. This test established that the signals of the two dipoles, are similar. Moreover, in order to evaluate antenna polarization properties, measurements were carried out by crossing the dipoles (fig. 1c) and by recording the traces every 90° of rotation around the axis *Y* of the transmitting antenna. In these conditions the signal power appeared very low, thus confirming a good degree of polarization of the two antennas.

The measurements of the radiation pattern were carried out by keeping the position of the receiver antenna stable, and rotating the transmitting antenna at 360° around the *y* axis at a sampling rate of 9°.

The reference position of 0°, with the orientation of axis *Z* parallel to the ground (see fig. 2) corresponds to referring the «back» of the T_x turned around towards the «front» of the R_x.

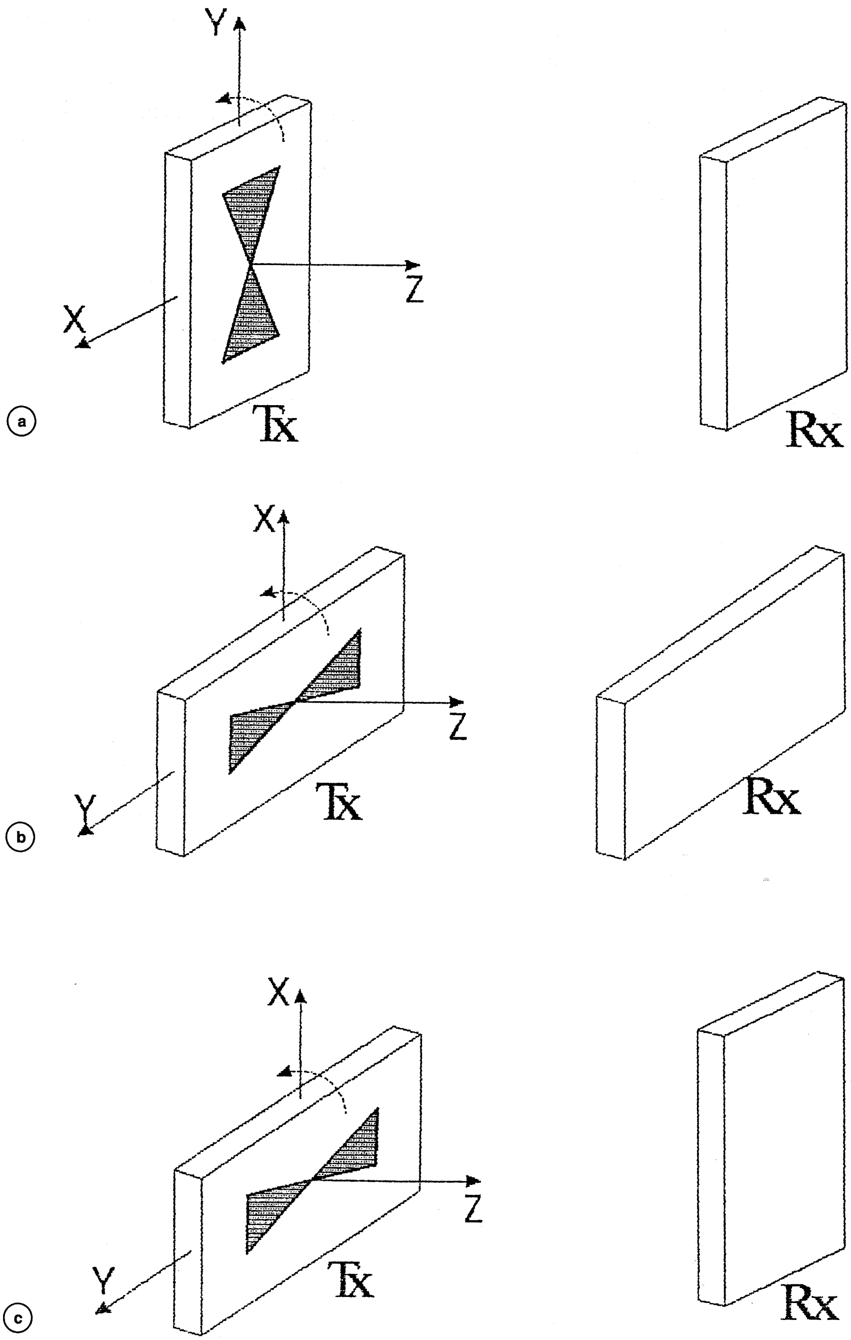

Fig. 1a-c. Schematic display of a planar dipole antenna (bow-tie). Plane *YZ* corresponds to plane *E* and plane *XZ* to plane *H*: a) and b) positions to determine the patterns on planes *E* and *H*; c) position to prove cross polarity.

From this position, the T_x was turned upwards until it was in the position «front to front», thus covering the first 180°. Subsequently, the two antennas were rotated 180°, around the Z axis and from this position the T_x was rotated the remaining 180° until it was brought back to the original position of «back to front». For each radiation pattern 42 reciprocal antenna positions were recorded analogically and digitally with a time interval which corresponded to about 50 scans.

4. Data elaboration and results

In order to calculate the radiation pattern, the traces were recorded analogically on the magnetic support and consequently converted into a digital form. With this type of format, each trace is composed of 1024 samples.

As previously mentioned, for every angular position of the transmitting antenna, about 50 scans were recorded.

The pulses received in each angular position of the transmitting antenna can be assumed to be proportional to the impulsive response of the system ($T_x + R_x$) multiplied by the directivity of the transmitting antenna in each individual position. Therefore, in order to evaluate the radiation diagram, it is necessary to calculate the power associated with the received signal, normalized in relation to the reference signal, that is, the one related to the antenna placed «front to front».

With the aim of determining this power from the signal, several problems related to both the presence of random noise and to the intrinsic fluctuations due to the instability of the system, were dealt with. These fluctuations mainly concern the origin of the temporal scale and the second part of the received signal P2 interval (fig. 3).

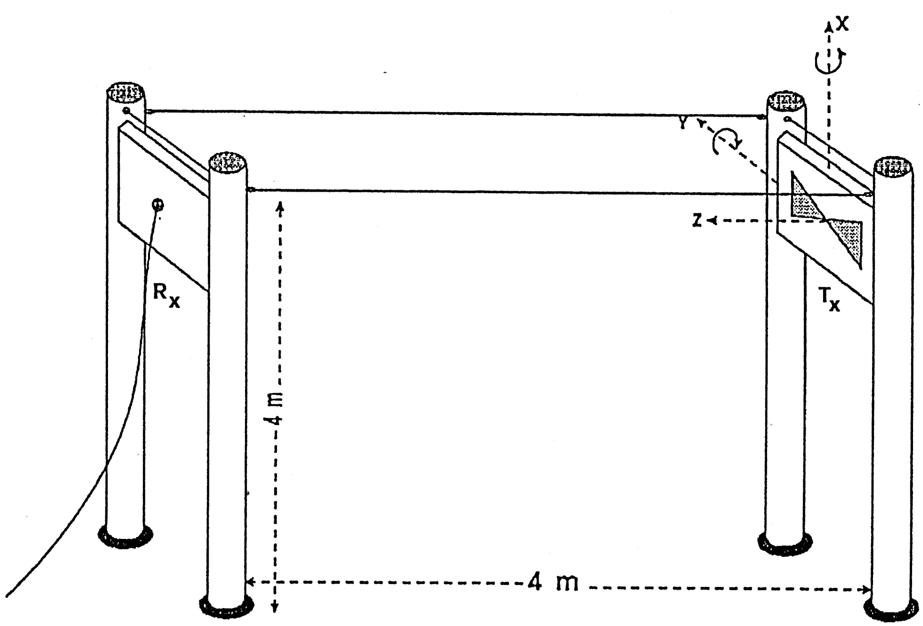

Fig. 2. Diagram of the experimental configuration set up to evaluate radiation patterns: R_x = receiver antenna, T_x = transmitter antenna.

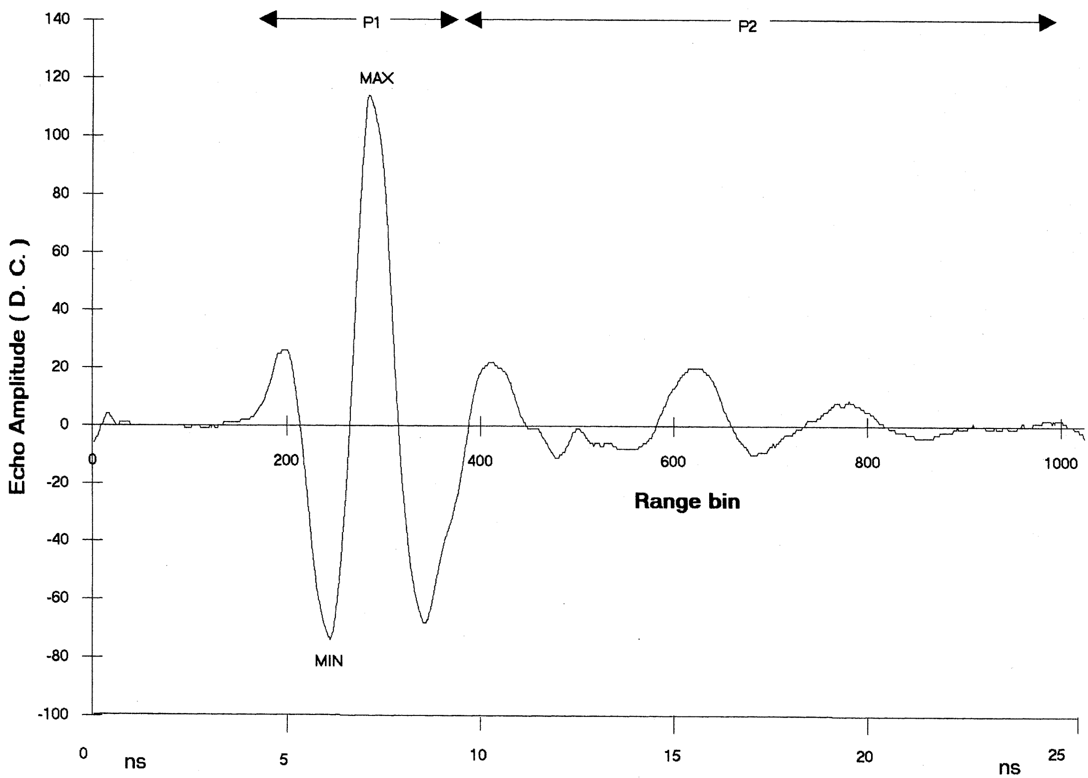

Fig. 3. Example of GPR traces, showing parameters employed to determine the patterns.

Figure 4 shows the frequency analysis of the received signal. The power spectrum (averaged according to the number of samples) is significantly different from zero in a frequency spacing of 600 MHz. The bandwidth at −3 dB is 200 MHz, while the maximum power corresponds to a value of 360 MHz. Because of the instability of the system, as previously mentioned, the components of the spectrum at a lower frequency appear to be less stable.

With the intention of comparing the shape of the radiation patterns, calculated by using different parts of the signal, different parameters relative to the recorded traces were taken into consideration.

Several methods for determining the signal power received at different angular positions of the transmitting antenna were tried out, in

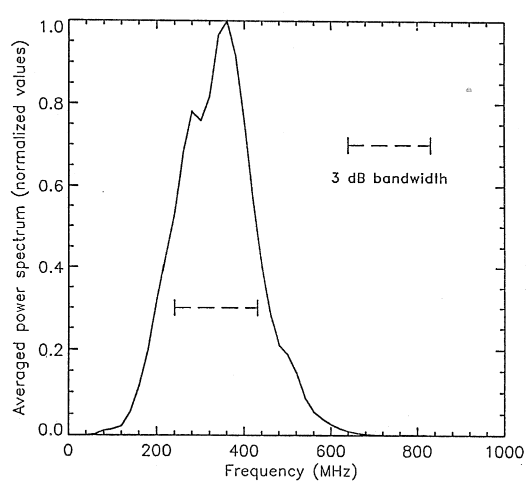

Fig. 4. Spectral analysis of the signal in frequency domain.

order to reduce the noise and instability effect. For this purpose the maximum and the minimum of the received waveform or the signal energy on a pre-determined time interval, were used as reference.

By using the whole time slot as an integration rate for calculating the signal energy, the results appear disappointing because of the previously mentioned instability, at the end part of the waveform.

In the phase of elaboration, the first operation was to align the selected traces, relative to each angular position of the antenna, using the maximum and the minimum (fig. 3) and to operate the stacking on 16 traces, in order to increase the S/N ratio. Subsequently, the zero level of the signal was estimated, using the first samples of the 25 ns time slot and then subtracted from the whole waveform. In this way, all the pulses were referred to the same origin with regard to both the temporal and amplitude scale and for each one values of absolute maximum and minimum amplitude and the energy in the P1 interval (fig. 3), were calculated.

The values thus obtained, normalized to those determined when the antennas were placed «front to front», are expressed in decibels (dB) and presented in polar form in figs. 5 and 6, relative to the radiation diagram on plane *E* and plane *H*, respectively. Each figure has three diagrams, obtained by taking into account the maximum, the minimum and the energy in P1, and in addition a fourth diagram obtained from the average of the previous ones.

From the analysis of the polar diagrams of plane *E* (fig. 5), several characteristics can be deduced concerning the antennas used.

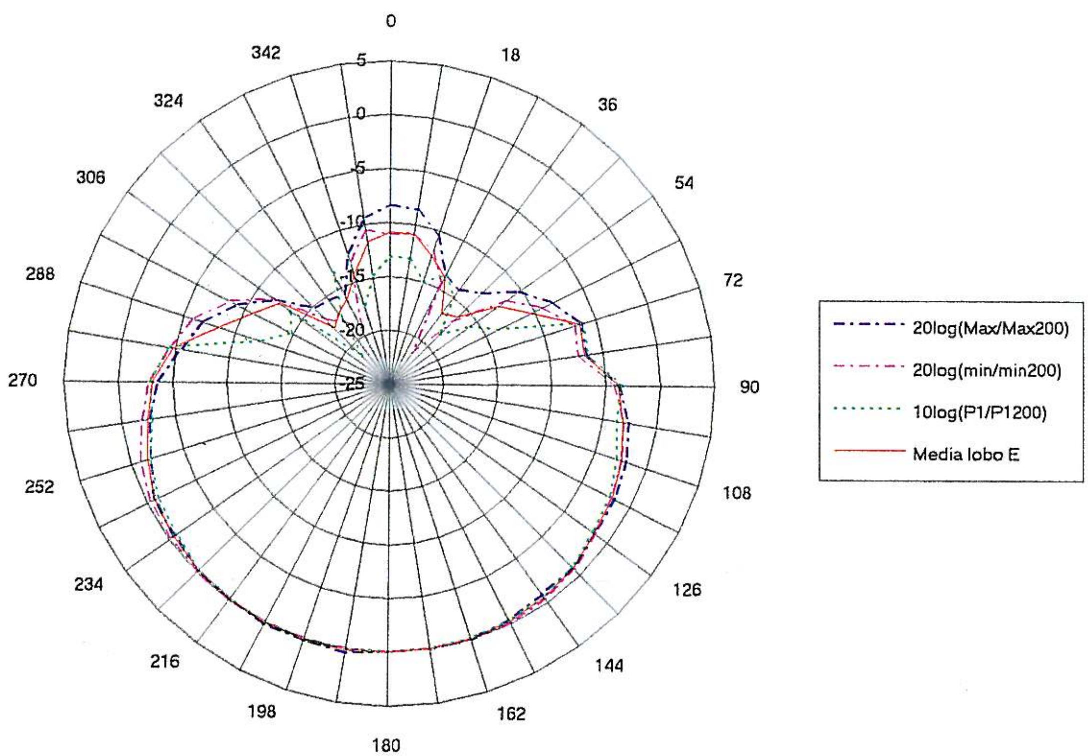

Fig. 5. Radiation patterns on *YZ* plane (plane *E*). The patterns obtained with various portions of the signal are shown, using different symbols.

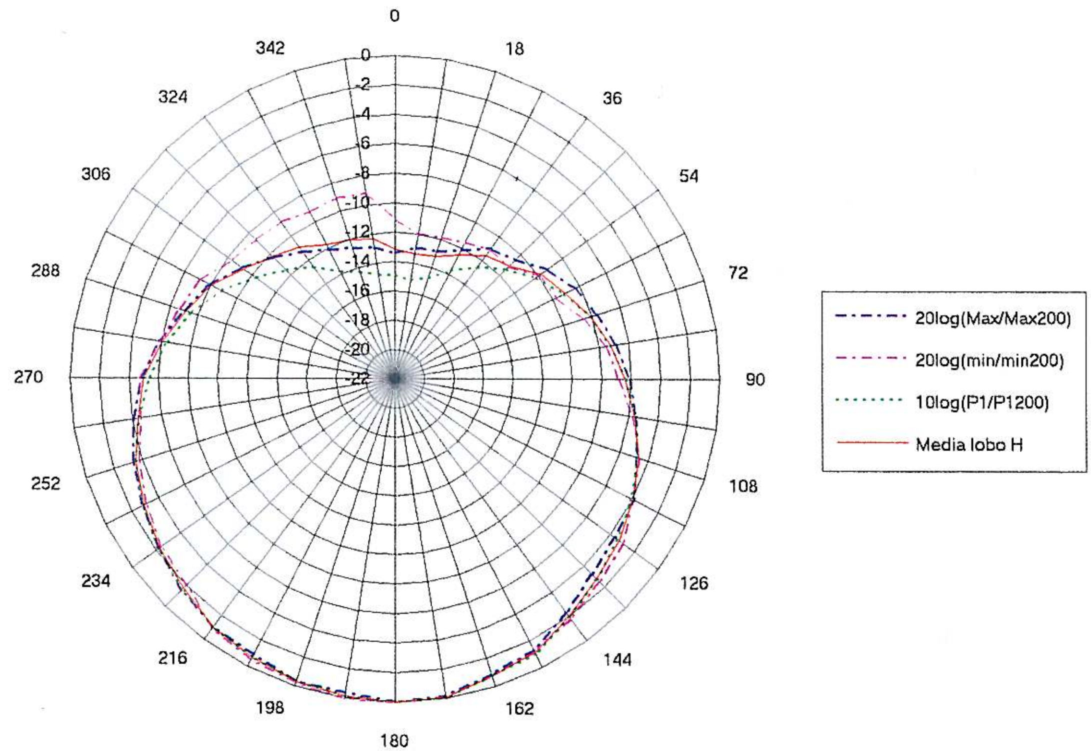

Fig. 6. Radiation patterns on planes *XZ* (plane *H*).

1) The main lobe is very regular and the different computation techniques provide coherent enough results. The diagram on plane *E* presents a greater width at −3 dB with respect to the *H*-plane diagram and moreover denotes a certain asymmetry of the lobe with respect to the geometrical axis of the antenna.

2) In the diagram of plane *E* a back lobe is present, in the radiation pattern at 0°. Even if slightly different according to the elaboration technique used, is however, lower than −6 dB. The energy irradiated posteriorly is very low (less than −14 dB) in the directions which are equal to about 306° and 43° which delimits the back lobe.

Even the patterns relative to plane *H*, calculated by using the same parameters, present common characteristics which can be deduced from the shape of the four polar diagrams (fig. 6):

1) the values relative to the back lobe, which at 0° are less than −8 dB, show the presence of a screening plane above the dipoles;

2) the shape of the back lobe is wide and does not present minor lobes;

3) the shape of the various diagrams of *H* radiation pattern appears on the whole to be less asymmetrical than that of pattern *E*; however, the direction with an amplitude −3 dB below the maximum seem to be rotated, on the diagram plane, in relation to the direction of reference *Z*.

The beam width at −3 dB is less than that calculated for lobe *E*.

Table I. Estimated antenna parameters.

Lobe	Lobe width to −3 dB		Backlobe dB		Maximum width respect to *Z*	
	E	*H*	*E*	*H*	*E*	*H*
Max	171°	115°	− 8.44	− 13.41	189°	180°
Min	170°	117°	− 11.14	− 11.11	198°	180°
P1	162°	115°	− 13.15	− 14.92	198°	180°

On account of the different techniques to determine the diagram, the width of the lobe at −3 dB, the width of the normalized directivity in the direction of the back (backlobe) and the direction of maximum directivity in relation to the geometrical axis of the antenna, are shown in table I.

5. Analysis of the results

The calculation of the radiation diagrams carried out by different methodologies, permitted the identification of the right parameters to use for evaluating the radiation patterns of GPR antennas in free space.

The analysis of the shape and characteristics of the pattern with regard to planes *E* and H, has shown how the diagrams, calculated using the absolute maximum, the absolute minimum and the energy related to the first part of the signal (P1 portion of fig. 3) can provide useful and reliable information concerning energy distribution.

The diagrams calculated on plane *E*, show a notable similarity in shape, of both the front and back lobes. The values relative to the front lobe practically coincide with the back lobe at an angle of 117° from $\theta = 117°$ to $\theta = 234°$. Outside of this interval the values relative to different lobes for each angular position, become progressively further apart until, corresponding to the position $\theta = 0°$, they reach a variation of almost 5 dB between the value calculated with the maximum (maximum backlobe) and that of the first power (minimum backlobe). The maximum difference between the two lobes, equal to more than 6 dB, does not correspond to the above mentioned position but to that relative to an angle $\theta = 315°$.

A similar observation can be made by analysing the diagrams of plane *H*. The shape of the radiation patterns is similar and the relative values of the front lobe practically coincide at the angle of 164° which ranges from $\theta = 99°$ to $\theta = 263°$. The values outside of this range become progressively further apart until, corresponding to the position $\theta = 0°$, they reach a difference of more than 3 dB between the value calculated with the maximum (maximum back lobe) and that calculated with the first power (minimum back lobe). In this case the maximum difference between the two lobes, equal to more than 5 dB, is found to corresponding with the position $\theta = 351°$.

In the case of both plane *E* and *H*, the smallest back lobe is obtained by the values of the first power P1, while the largest is relative to the lobe calculated by the maximum and the minimum, respectively. The fluctuations observed on the patterns could be due to different factors, partly deriving from a slight signal instability and partly due to the global structure of the antenna.

Noise incidence and measurement errors are greater when evaluating radiation in back directions, where the signal/noise ratio is smaller. The presence of a back lobe in the diagram fig. 5, could be due to the external cover, the presence of connecting elements between the coaxial cable and the dipole and other possible electronic devices inside the antenna cover which in some way modify the radiation pattern.

The average lobe on planes E and H, has been calculated by using the three lobes. It can be assumed an accurate estimation of the geometrical radiation distribution of the front lobe. On the other hand, the dispersion of the data relative to angles which are less than 90° and more than 270°, especially when calculated on plane E, renders the average lobe less representative of the spatial distribution of the radiation, in this angular range.

6. Conclusions

The experimental methodology used to reconstruct the radiation patterns of GPR antennas, even though they are experimental prototypes without the use of particular equipment, permitted useful information to be collected in terms of the instrumentation employed.

Analysis of the results showed that the antennas employed have a quite wide main lobe, a rather limited back lobe and good similarity.

Further experimental tests are at an advanced stage to determine and study the following: on the one hand the shape of the reflected pulse from geometrically known targets, placed in free space and in the ground, and on the other hand the phenomenon of wave propagation in the field, near to and far from the antenna.

The knowledge of the radiation pattern of the GPR antenna therefore, appears to be necessary in order to understand phenomena connected to electromagnetic pulse reflections, as well as to be able to realise appropriate modeling which is useful for a better interpretation of experimental data.

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