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INTRODUCTION TO GPR PROSPECTING

1.1 WHAT IS A GPR?

Ground-penetrating radar (GPR), also known as surface-penetrating radar (SPR) (Daniels, 2004), is literally meant as a radar to look underground. Actually, it is used to look into both soils and walls and, recently, even beyond walls.[1]

In principle, the GPR can be viewed as composed by a central unit, a transmitting antenna, a receiving antenna, and a computer. The central unit generates an electromagnetic pulse or, more generally, an electromagnetic signal that is radiated into the soil by the transmitting antenna. The signal is radiated in all directions, but most energy is radiated within a conic volume under the antenna, as shown in Figure 1.1. When the electromagnetic waves meet any buried discontinuity (a buried object but also the interface between two geological layers, a cavity, a zone with different humidity, etc.), they are scattered in all directions according to some pattern depending on the buried scenario. Consequently, they are partially reflected also toward the receiving

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[1] Actually the instruments that perform the so-called "through wall imaging" are not customarily considered GPR systems. However, we can say that conceptually they are at least a hybrid between a radar and a GPR.

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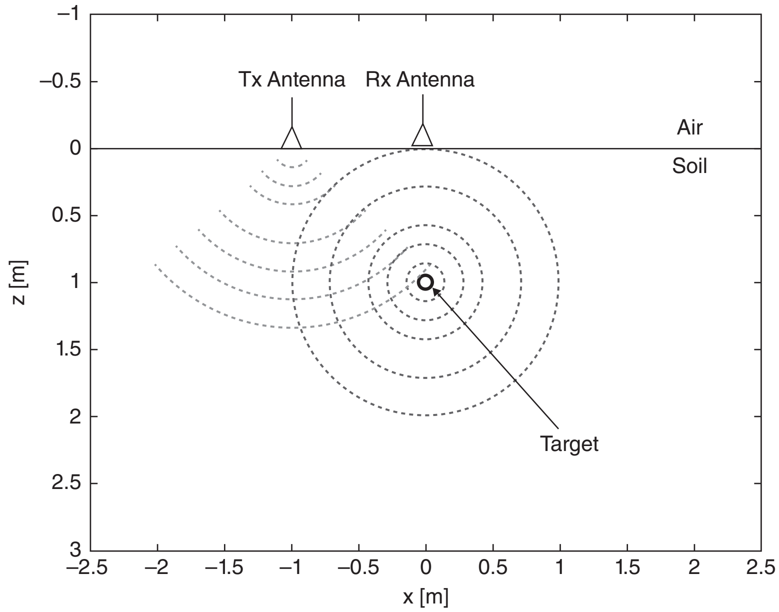

Figure 1.1. The working principle of a GPR.

antenna, again according to Figure 1.1. More precisely, Figure 1.1 is intended to be the central cut of a three-dimensional scenario.

Usually, both the transmitting and the receiving antennas are incorporated into a rigid structure[2] and move together. The gathered signal is customarily represented in real time on the screen of the computer[3] and is stored in the hard disk of the computer. It is implicit that the equipment of a GPR also includes suitable cables to connect the central unit, the antennas, and the computer, along with a device to provide energy in the field. The energy is usually supplied by rechargeable batteries in the form of a zero-frequency electrical voltage. The central unit transforms this energy into a signal in the microwave frequency range. Modern systems are often also equipped with a GPS, in order to geo-reference the probed areas.

In Figure 1.2, a photograph of a GPR is shown, and the main components are put into evidence. The trolley is facultative, but extremely useful for prospecting on the soil. Usually, the antennas are also equipped with an odometer that allows us to measure the covered distance.

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[2] The couple of antennas is often enclosed in a unique box, and the whole box is improperly called the “GPR antenna.”

[3] In the past, other recording systems were exploited as described in Daniels (2004) and in Jol (2009), because the GPR was invented much earlier than the laptop.

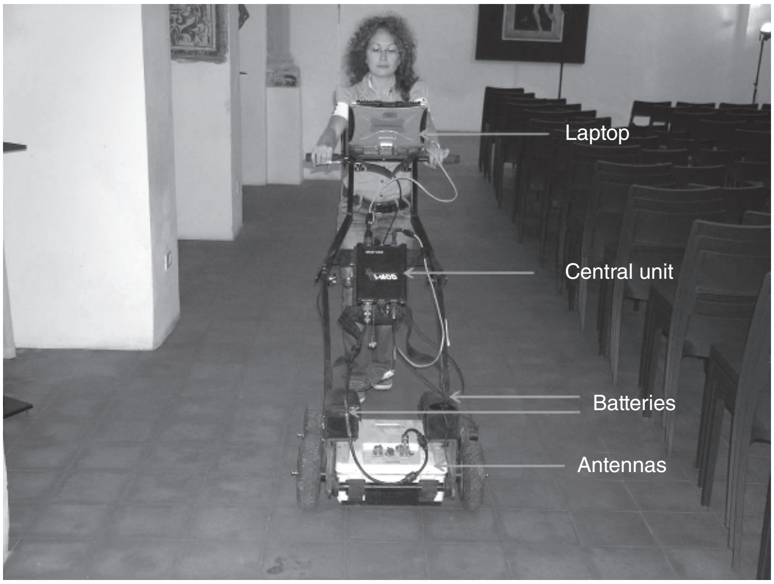

Figure 1.2. Photograph of a GPR (a Ris Hi Mode system) equipped with a double antenna at 200 and 600 MHz antenna.

The odometer is an important detail, because it allows us to compensate for the natural nonuniformity of the velocity of the human operator while driving the GPR: that is, it allows us to achieve a uniform sampling of the GPR signal along the observation line.

However, in some cases it is impossible to make use of the odometer—for example, because the prospecting is on a sandy area that hinders the rotation of the wheel. In these cases, periodical markers have to be recorded along the observation line, which is partitioned into segments of known length. The velocity of the instrument (and thus also the sampling) is considered constant within each segment but not along the entire observation line.

The working principle of a GPR is the same as that of a conventional radar. However, there are meaningful differences between the two instruments, in terms of technologies, exigencies, applications, and frequency bands (Daniels, 2004; Levanon, 1988). In particular, unlike the conventional radar, usually a GPR has to identify static targets, and in most cases the interpretation of the data is not requested in real time. On the other hand, in GPR prospecting the electromagnetic waves do not propagate in air but instead propagate in more complicated host media, customarily lossy and inhomogeneous, possibly dispersive, and in some cases anisotropic and/or magnetic (Daniels, 2004; Jol, 2009; Conyers, 2004). Last but not least, in GPR prospecting the characteristics of the host medium are usually not known a priori and have to be estimated from the data, as described in more depth in the next chapter.

1.2 GPR SYSTEMS AND GPR SIGNALS

There are essentially two kinds of GPR systems: the pulsed one and the stepped-frequency one. A pulsed GPR system radiates and receives the echoes to electromagnetic pulses. On the other hand, a stepped-frequency GPR decomposes the electromagnetic pulse into its spectral components and radiates them sequentially. Consequently, it radiates and receives trains of sinusoidal signals. The soil and the buried targets usually have a linear behavior with respect to the radiated GPR signal, in the sense that the signal scattered by the buried targets is a linear quantity (more details will be given in Chapter 6) with respect to the incident signal. Moreover, the soil can usually be considered a time-invariant medium within the time needed for the GPR measurement campaign. This makes the pulsed and the stepped-frequency GPRs theoretically equivalent. In practical terms, however, stepped-frequency systems are generally claimed more performing (Noon, 1996), even if the pulsed systems are quite more common and their technology has been assessed for a longer time. So, the debate about what kind of system is really the best one (or at least the most convenient one in dependence of the application) is still open. In this text we will not enter such a debate, which is mainly based on technological aspects, but will deal with both some analytical and practical aspects of the GPR prospecting in relationship with both systems. In particular, whatever the system, the GPR signal can be regarded as a function of the spatial point and of the time or the frequency indifferently, because of course we can Fourier transform pulsed GPR data in frequency domain and we can back-Fourier transform stepped-frequency GPR data in time domain.

Following a widely accepted terminology (Daniels, 2004), the GPR data relative to a single spatial point will be labeled as an A-scan or just a GPR trace, and the comprehensive set of GPR traces relative to an entire scanned line will be labeled as a B-scan. A B-scan corresponds to a matrix of numbers: N time (or frequency) samples times M spatial positions—that is, M traces each of which discretized into N samples. This is equivalent to assuming that the GPR "stops" in each A-scan position, gathers the data in that position, and goes on to the next position. Actually, in most cases the data are gathered in continuous mode—that is, the GPR gathers the data while moving—but the model "stop-gather-and-go-on" is in most cases acceptable because of the huge difference between the velocity of propagation of the electromagnetic signal and the velocity of the human operator, even if the time required to store an A-scan is actually quite longer than its formal time bottom scale. This happens because of several reasons such as sequential sampling (for pulsed systems), integration time of the harmonics (for stepped frequency systems), and stacking (for both). Here, we will not focus on these aspects, which are mainly technological and already explained elsewhere (Noon, 1996; Daniels, 2004; Jol, 2009). Let us just restrict ourselves to say that a nonexcessive (the quantification is case-dependent) and constant velocity during the data acquisition is always a good rule of thumb. The comprehensive set of GPR data relative to a series of parallel B-scans is usually labeled as a C-scan. In general, what is immediately visualized in the field is a B-scan in some color or gray tone scale. These data, usually called raw data, can allow us to identify targets of interest, but in general the image and its interpretation can improve meaningfully after a suitable processing.

1.3 GPR APPLICATION FIELDS

A meaningful overview about the GPR applications is beyond the purposes of this book and is not its goal. Notwithstanding, for sake of self-consistency, a brief outlook is provided.

Within the field of the archaeology (Conyers, 2004), GPR can allow us to identify the areas with alleged interesting buried remains, which in turn allows us to avoid an exhaustive and expensive (sometimes too expensive) excavation. Another issue of interest is the field of the preventive archaeology—that is, the preventive prospecting of areas where something is going to be built (a road, a building, an underground station, etc.). This mitigates the risk of destroying archaeological sites and also mitigates the economic risk that the works will be stopped by some Cultural Heritage Institution.

Monitoring of monuments as historical buildings, statues (Sambuelli et al., 2011), ancient fountains, historical bridges (Solla et al., 2011), and so on, is another subject of interest. In particular, GPR monitoring (possibly integrated with other geophysical investigations) can give information about the state of preservation of the monuments and can provide useful information in order to address a restoration project properly. In some cases, information of historical interest can also be achieved—for example, about the presence of walled rooms, crypts, hypogeum rooms, tombs, hidden frescoes, and so on (Pieraccini et al., 2006; Grasso et al., 2011).

GPR prospecting is also exploited in civil engineering (Grandjean et al., 2000; Utsi and Utsi, 2004). In particular, it can be used to identify structural damages and to investigate about hidden structures like sewers or water and gas pipes, whose presence is in many cases not precisely documented.

Demining is another important application. In particular, modern mines are customarily built with plastic materials with only little or even no metallic parts. Therefore, they are often hardly visible or completely invisible to a metal detector. Moreover, a metal detector is not able to provide all the details possibly available from a GPR system, namely the position (in particular the depth), the size, and (among certain limits) the shape of the buried target. Demining has been dealt with for years within the GPR community (Groenenboom and Yarovoy, 2002), and it has also been successfully performed many times (Sato and Takahashi, 2009).

GPR prospecting is also exploited for asphalt monitoring.[4] In particular, it is possible to identify subsidences or damaging before they become worse or even dangerous for drivers and pedestrians. These problems are even more pressing in areas where the roads frost in the winter and thaw in the spring (Hugenschmidt et al., 1998; Villain et al. 2010).

In several application fields, it can be particularly useful to make use of advanced GPR systems equipped with a large array of antennas (Sala and Linford, 2010; Böniger and Tronicke, 2010). These systems can gather simultaneously several (up to 14 and more) measurement lines with a unique *going through*. On the other hand, these systems need a quite flat scenario to provide good performances, because the arrays are rigid and possibly quite large (up to 2 m and larger).

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[4] In this case, the antennas are usually mounted on a car.

GPR prospecting is also applied with regard to mines and pits. In particular, it can help to identify shallow veins of the mineral of interest (Ralston and Hainsworth, 2000; Francke, 2010) and can even help with regard to some safety issues. In fact, fractures, water infiltrations, or just obsolescence can badly affect the stability of the structure, in mines as well as in tunnels (Grodner, 2001; Cardarelli et al., 2003). In some cases, even explosive gases trapped in natural cruets can be met while digging, especially in coal mines (Cook, 1975).

Another application of interest is GPR prospecting on the ice (Arcone et al., 2005). In particular, polar ice contains information about the geological history of our planet and can also provide information about the occurring climatic and environmental changes. GPR prospecting can be successfully performed on both fresh and salty ice.

GPR prospecting on fresh water is a field of interest too—for example, for sedimentology applications in relationship with the bottom of lakes, ponds, or rivers[5] (Smith and Jol, 1997). Liquid seawater, instead, is customarily too lossy to allow a reliable GPR prospecting.

Industrial agriculture is another applicative field where it is of interest to devise an intelligent exploitation and distribution of the water (Friedman, 2005). In this framework, GPR can be a useful tool for the evaluation of the electromagnetic characteristic of the shallower layers of the soil, and in particular its dielectric permittivity. Some semiempirical relationships (Topp et al., 1980) can in some cases allow us to estimate the water content from the dielectric permittivity.

Let us also mention the subject of the GPR investigation on Mars,[6] where unmanned vehicles are gathering data, mainly looking for water and, consequently, the possible (current or past) presence of life (Picardi et al., 2005).

Finally, let us also prompt (a) forensic applications, where, for example, buried corpses or hidden weapons are looked for (Hammon et al., 2000), and (b) borehole prospecting (Ebihara et al., 2000), where antennas are lowered in one (reflection mode) or two (transmission mode) carrot-holes.

1.4 MEASUREMENT CONFIGURATIONS, BANDS, AND POLARIZATIONS

GPR data are mostly taken in reflection mode and, if possible, the antennas are preferably in contact with or at very short distance from the structure to be probed. However, in some cases the data are necessarily moved in a contactless configuration—as, for example, in demining (Sato and Takahashi, 2009) and asphalt monitoring (Hugenschmidt et al., 1998) or also for the monitoring of works of art that cannot be touched (Pieraccini et al., 2006).

In most cases, the antennas are rigidly placed in a unique box and move together, but in some cases the two antennas can be moved separately from each other. This is a

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[5] In this case, the antennas are usually mounted on a boat.

[6] In the past also GPR data from the Moon have been analyzed.

valuable resource, especially in order to measure the electromagnetic characteristics of the soil by gathering common midpoint (CMP), wide angle reflection and refraction (WARR), or trans-illumination data (Davis and Annan, 1989; Daniels, 2004; Conyers, 2004; Jol, 2009). Actually, sometimes the WARR configuration (also called multistatic multiview) is exploited not only to measure the characteristics of the soil but also to improve the image of the buried scenario. However, this is unpractical on a large scale, and the improvement achievable on the image is usually quite marginal, because the information achievable from the spatial diversity is not independent from that achievable from the frequency diversity (Persico et al., 2005; Persico, 2006).

Customarily, the electromagnetic characteristics of the soil and/or of the buried targets also depend on the frequency. This is expressed by saying that the soil (more in general the propagation medium) and/or the targets are dispersive. Several dispersion laws are known (Lambot et al., 2004), but it might be not easy to establish in the field what is the most suitable dispersion law for the application at hand. Therefore, as a matter of fact, in most cases the dispersion is not accounted for in the data processing. More precisely, we can say that the dispersion phenomenon is more often considered if the purpose is to characterize the propagation medium in itself, and more rarely if the purpose is to focus the targets embedded in it.

In general, the needed band of frequencies depends on the particular application. Customarily, as is well known, lower frequencies penetrate the opaque structures better than higher frequencies but provide a worse image of the targets. This drives us to use low frequencies (below 200 MHz) if the required investigation depth overcomes 5–7 m or more (e.g., in some geological applications), radio frequencies (200–700 MHz) for applications where the depth to reach is of the order of 3 m (e.g., in most archaeological prospecting), higher radio frequencies (700–3000 MHz) for applications where the maximum required depth of investigation is of the order of 1 m (e.g., detections of fractures or asphalt monitoring), and sometime even higher microwave frequencies if the maximum investigated depth can be limited to the order of 50 cm (e.g., demining or determination of the water content in the shallower layers of the soil). This classification is sketchy: It just indicates an average distribution, and many exceptions might be found. In particular, it refers to GPR application in “temperate” soils: The ice constitutes an exception and can allow a much deeper penetration of the GPR signal. In general, the maximum penetration depth depends on the current case history and can be estimated in the field, on the basis of the data.

Several kinds of antennas are exploited in GPR prospecting. For the low-frequency cases, below 200 MHz, the antennas are customarily unshielded loaded dipoles, often quite long (depending on the central frequency, they can be up to 3 m long and even longer). The fact that the antennas are unshielded makes them gather reflections from targets in air too, and it makes the results more vulnerable to the electromagnetic interferences from external sources. On the other hand, a shield would make them quite weighty. Instead, beyond 200 MHz the GPR antennas are customarily shielded. In the range 200–1000 MHz, the most widely exploited antennas are probably the bow ties (Lestari et al., 2004), that are linearly polarized and customarily are fed with a coaxial cable. Sometimes a circular polarization can help for the discrimination of some targets. In these cases, large band spiral antennas (Daniels, 2004) can be used, even if their use is more rare. At higher frequencies, Vivaldi antennas and horns (Gentili and Spagnolini, 2000; Pieraccini et al., 2006) can be exploited too. They are linearly polarized and can be fed by a waveguide, which makes them more robust and suitable for high-frequency applications (Stutzman and Thiele, 1998). In some cases, the GPR system is equipped with an array rather than just a pair of antennas (Sala and Linford, 2010; Böniger and Tronicke, 2010). In these cases the single elements of the arrays are usually dipole-like antennas.

1.5 GPR DATA PROCESSING

The processing of GPR data is a large topic, and in particular the current application can require or at least can make more suitable some strategy with respect to some other. In particular, two fundamental categories of processing can be distinguished, namely deconvolution-based (Jol, 2009) processing and SAR effect-based processing. In deconvolution-based algorithms (also called 1D), one essentially processes the single GPR traces trying to retrieve the shape of the radiated pulse—that is, trying to equalize the distortion that the radiated pulse suffers because of the propagation in a dispersive inhomogeneous medium and because of the scattering from the target. This kind of processing is important especially in cases when the targets looked for have a foreseeable "signature" and tend to distort the impinging pulse in a known way. Examples of deconvolution-based processing in relationship with demining problems are probably the most common ones: In particular, usually the main trouble in this case is not to identify the mine (even if the difference between the dielectric characteristics of a plastic mine and those of the surrounding soil might be low), but rather to reduce the false alarm probability—this is, the probability to confuse the mine with any other target characterized by the same order of size and average depth (Timofei and Sato, 2004). In such a situation, a deconvolution can help in discriminating the nature of the reflecting target. The second category, which here will be labeled as SAR effect-based [the acronym stands for synthetic aperture radar, (Daniels, 2004)], is concerned with a processing that regards all of the traces within a B-scan or a C-scan and is aimed to focus within a vertical plane (2D models) or in a buried volume (3D models) the targets embedded in the host medium at hand. Within these SAR processing, it is then possible to distinguish a plethora of models and related algorithm, based on different kinds of approximation of the scattered field. In particular, there are linear algorithms based on the Born approximation (Chew, 1995), on the Rytov approximation (Devaney, 1981), on the extended Born approximation (Torres-Verdin and Habashy, 2001), on the Kirchhoff approximation (Liseno et al., 2004), and so on. Moreover, there are nonlinear approximations as the second-order Born approximation (Leone et al., 2003) or iterative algorithms that update up to convergence (according with some Cauchy-like criterion) the result of a single-step processing. Customarily, in these cases the single-step processing is linear (Moghaddam and Chew, 1992), but the comprehensive algorithm is nonlinear. There are also fully nonlinear approaches, based (for example) on the statistical minimization of some cost functional (Caorsi et al., 1991). Finally, let us list also the linear sampling method (Colton et al., 2003), a fast nonlinear inversion algorithm based on single-frequency multiview data that has been becoming popular in recent years.

Actually, most of these 2D and 3D models have been developed in a context wider than that of GPR data processing, which is the literature on microwave inverse scattering. Notwithstanding, they can be applied (in several cases they have been already applied) to the reconstruction of targets embedded in the soil or in masonry, which we can classify as a GPR application. Their utility and the trade-offs between them are related to the many possible specific applications.

In this text, we will focus only on GPR data processing based on the Born approximation. In particular, the core of the processing dealt with here will be the migration (Stolt, 1978; Schneider, 1978; Yilmaz, 1987) and the linear Born model-based inversion (Colton and Kress, 1992) algorithms, both of which considered either in a 2D or in a 3D framework. Let us also specify that, commonly, the 3D processing is meant as the suitable joining of several 2D results achieved from several B-scans. This is useful and practical, especially (but not only) in order to image horizontal buried layers where the plan of built structures can be identified (Conyers, 2004). However, rigorously this is not a 3D processing method. We will label it a pseudo-3D approach, in order to distinguish this method from a real 3D approach, that will be dealt within Chapters 11–13. A 3D approach is theoretically more refined than a pseudo-3D one, but it is also more difficult and computationally more demanding.

Let us outline, however, that, even if only these linear data processing will be dealt with, the complete scattering equations are derived, so that the intrinsic nonlinear nature of the scattering phenomenon is shown.

Several reasons underlie the choice to limit our discussion to linear Born model-based processing. First, an adequate discussion of all the listed techniques would require a book quite long (at least four times the size of the current book). Second, in the common GPR praxis the most exploited focusing algorithm is undoubtedly the migration, also because there are several commercial codes able to implement it. Third, we have preferred to give space to some extra topics that are not inverse scattering issues but, in the real world, are inseparable aspects of GPR data processing, namely the indirect measure of the characteristics of the embedding medium (that in general are not known a priori), the extraction of the scattered field data from the total field data, and some aspects specifically related to the gathering of the data either with a pulsed- or a stepped-frequency GPR system.

Let us outline that the GPR processing is not constituted by a mere focusing. For example, data filtering and gain variable versus the depth are often very important passages. It is also worth outlining that some practice in the field is unavoidably essential (better if the starting phase is performed with the assistance of a more skilled user): there is no book that can replace it.

The main aim of this text is to focus on some of the theoretical aspects that seem to the author particularly important for an “aware”execution of a GPR measurement campaign, followed by a proper processing and, when possible, a reasonable interpretation.