GPR (Ground Penetrating Radar) into Real World

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Abstract

GPR (Ground Penetrating Radar) is one of subsurface sensing technologies, which has been used intensively since 1980s. Due to rapid development of both hardware and software, its possibilities have been considerably extended resulting in widening the area of its applications. While such applications as to detection of buried pipes and cables, archaeology and geology are established category, new applications such as humanitarian demining and Luna and Mars observation are gathering interests. Even in the classical applications, technology development is required to improve GPR performance in terms of faster data acquisition, deeper penetration into ground and subsurface object characterization. In this tutorial talk, we will introduce the most modern GPR systems and demonstrate technology development due to challenges of new applications.

1. Introduction

GPR has been extensively applied to investigate subsurface structures or buried objects in geology, archaeology, civil engineering, environment and soil engineering since 1980s [1-3]. Owe to the development of PC and other hardware and software technologies, this non-destructive method of subsurface sensing is becoming increasingly important for many environmental and shallow geophysical applications. GPR can quickly and accurately determine the subsurface structure. GPR equipments can easily move on the ground surface, so it is suitable for survey in vast area. Compared to its practical value, we are afraid this technology is not well known among scientists and engineers working on radar and electromagnetics. In this paper, we introduce first the fundamental of GPR and after that discuss new GPR technologies and some of emerging applications.

2. Fundamentals of GPR

2.1 Frequency and Applications

The dielectric constant of subsurface material consists from rocks and soil varies by the constitution material its selves, however, the dielectric constant of these material have similar value, and the water contained in the material is most significant in the dielectric constant. We can understand that any changes of water condition in the soil and geological formations can cause the reflection of electromagnetic wave, and it is one of the reasons that GPR is very effective sensor for subsurface measurement. However, water in material always induces electrical conductivity, which causes the attenuation of electromagnetic wave. Generally, higher frequency electromagnetic wave in material is suffered from higher attenuation. In order to achieve high resolution in radar, we need wider frequency range. However, in order to achieve longer penetration depth, we have to use lower frequency. Therefore, most of GPR systems operate in the frequency range from DC to the highest frequency, which can reach to the buried objects. Thus, GPR is very wide frequency system, and its center frequency is refereed as its operational frequency. In other word, GPR has been UWB radar from the beginning. Typically, GPR for detection of buried objects such as metal pipes use the frequency around 300-700MHz, where the size of the object is about 10cm, and 1-2m in depth. GPR for concrete inspection operates around 1-1.5GHz, where the object is 1cm large and depth is 20-50cm, and GPR for humanitarian demining, operates around 2-3GHz, where the depth of the target is shallower than 20cm. Selection of operation frequency is essential in GPR survey design.

2.2 Hardware and Antenna

In order to cover large bandwidth GPR uses either time domain or frequency domain UWB technology [4]. The frequency domain approach has a solid background: the well-developed RF technology, and a large choice of commercially available components. Depending on the way of transmitting different frequency components (sequential or simultaneous), the frequency-domain approach can be realized using either stepped-frequency continuous wave

(SFCW) or OFDM methods respectively. For a fixed value of the peak transmitted power, the frequency domain approach typically leads to a higher signal-to-noise ratio due to a higher and more uniform spectral density of the radiated signal, more accurately measured data and, in principle, it allows for a much larger frequency bandwidth than the time-domain approach. However, the frequency domain approach requires more bulky and more expensive equipment and a larger measurement time. It also involves very precise calibration of the whole radar chain, which is necessary for numerical synthesis of short pulses in the post-processing.

In the time-domain approach, radar physically transmits short pulses without a carrier frequency (so-called video pulses). The time-domain radars are relatively simple, relatively cheap and robust. Due to these features, first GPR have been built base on the time-domain approach. The weak points of the time-domain approach are overstressed systems due to large peak-power values, a low signal-to-noise ratio and typically low accuracy of the measured data.

A few hybrid technologies, in which strengths of both frequency-domain and time-domain approaches are partly combined, have been developed over last few decades. Among these technologies we can mention frequency-modulated continuous wave (FMCW), (quasi)-noise and maximal length binary sequence (MLBS or M-sequence) radars.

Successful transmission of electromagnetic energy into the ground requires use of dedicated antennas. Such antennas should possess ultra-wideband operational frequency band and, if used at time-domain radar, should have linear phase characteristic over whole operational band. Over decades almost all known types of ultra-wideband antennas have been used to GPR. First of all due to practical limitations (such as antenna size and weight) and due to good coupling to ground, resistively loaded dipoles and loaded bow-tie antennas became the most popular antenna types for GPR. At frequencies above roughly 300MHz such antennas are often shielded to decrease radiation into air. In applications, which require operational frequencies above roughly 1GHz, different modifications of TEM horns, tapered-slot (Vivaldi) antennas and cavity-backed spirals are often used. These antennas allow for high radiation efficiency.

Being in vicinity of GPR antenna, ground has a strong influence on antenna performance, which becomes apparent in the following phenomena. First, ground decreases the input impedance of planar antennas (such as dipoles, bow-ties, spirals, etc.). Depending on antenna elevation above the ground and dielectric permittivity of the ground, this decrease of the input impedance can reach up to 100Ohms. Second, ground performs efficient resistive loading of antenna aperture. This typically results in decrease of antenna late-time ringing in time-domain and smoothening of the antenna transfer function in frequency domain. Third, ground changes directive properties of antenna by decreasing radiation into air and increasing radiation into ground. Finally, ground causes focusing of transmitted into ground radiation. This can bee seen as decrease of the antenna footprint size.

3. New Technologies in GPR

3.1 Imaging

GPR acquires signal traces one by one while it moves along a survey line. Normally, 2-D GPR profile is obtained directly from the raw data sets. However, due to the size limitation of GPR antenna, which can be used for data acquisition, radiation pattern of GPR antennas is very wide. Therefore, the raw GPR signal does not show the original shape of the scattering objects due to scattering and diffraction. In order to estimate the true profile of the subsurface objects, we have to process GPR signals. Targets of GPR measurement normally does not move. Therefore, data sets acquired along a survey line can be processed for imaging afterwards. This is one kind of synthetic aperture processing, or migration. Thanks to the high performance of PC, image processing on site is now easy, and 3D image reconstruction is possible. However, in order to achieve sophisticated signal processing for image reconstruction, accurate sensor positioning is essential. For example, Grasmuek and Viggiano [5] proposed a method using laser position sensors and showed very accurate 3-D GPR images. Sato proposed a simple sensor tracking system for a had-held GPR, and showed its capability of imaging of buried landmines [6].

The other important factor for GPR signal processing is suppression of clutter. The clutter is caused from the ground surface reflection and inhomogeneity in soil. Therefore, increasing transmitting power does not increase the S/N ratio in GPR. Small change of moisture in soil can be detected by GPR. Generally, migration (SAR-like) processing also suppresses the clutter.

3.2 Polarization

As GPR technology has accommodated operational approaches and many signal processing methods from seismic geological prospecting, often vectorial nature of electromagnetic field is neglected by GPR users. However polarization of electromagnetic waves contains often important additional information over buried scatterers and polarimetric features can be used for classification of detected targets. Two eigenvalues of polarimetric scattering matrix determine the polarimetric anisotropy of the target and are independent of its orientation. For polarimetrically isotropic targets, like any body of revolution whose rotation axis is vertical, both eigenvalues are identical. Such targets do not cause depolarization of the scattered field at any orientation of a target. For a strongly anisotropic target (like a cable), one of eigenvalues is much larger than another one. Orientation of such targets can be determined from polarimetric analysis.

The polarimetric A-scan analysis can only be applied in the case where the target response does not overlap in time with a signal coming from another direction from another target. A standard procedure to separate responses from different targets is migration. Cross-polarized images of rotationally-symmetrical targets (like disks) have non-zero intensities; they have a circular shape with minimum intensity values the in E- and H-planes of the antenna system. These minima are determined by the cross-polarimetric isolation of the antenna system. For polarimetrically anisotropic targets (like the barbed wire, pieces of metal with arbitrary shape, etc.) there is no clear minimum in the center of the cross-polarized image. In this case, the intensity value at the center of the cross-polarized image provides the actual magnitude of depolarized component of the scattered field.

Also in bore-hole GPR near-field polarimetry has been successfully used by Sato to classify different fracture types [7].

3.3 Digital array footprint forming

An alternative to the synthetic aperture imaging is an imaging with an antenna array with simultaneous operation of antennas. Footprint focusing in such systems is performed digitally by simultaneous processing of data coming from receive antennas. The antenna system may include a single transmit antenna and linear array of receive antennas [8]. Such approach simplifies the antenna system and considerably simplifies the electronics. Imaging by focusing arrays leads to drastic decrease of the data acquisition procedure and improves image quality due to elimination of mechanical positioning errors. At the same time this approach requires design of dense UWB antenna arrays with extremely low coupling between antenna elements.

4. New Applications

Recent developments of GPR technology expand its area of applications. Some of emerging applications are described below.

4.1 Humanitarian Demining

It has been demonstrated that UWB radar is useful in a multi-sensor system dedicated to landmine detection, especially for humanitarian demining [9]. Numerous field trials of different sensors have proven that while for most ground types, sensor can achieve a desirable detectability level, a decrease of false alarm rate remains the most important task for sensor developers. This decrease can be achieved only via classification of detected targets and differentiation between landmines and friendly objects. Target classification requires accurate measurements of the electromagnetic field scattered from the subsurface. This qualitatively new demand makes the principal difference between usual GPR and GPR sensor for landmine detection: the first one should just detect the field scattered from a buried target (i.e. distinguish this field from all other electromagnetic fields), while the second one should measure it accurately (i.e. determine the scattered field waveform). From the measured values of the scattered field different methods can be used to determine localization, size, shape, dielectric permittivity and other features of a buried target. Based on these features target classification can be performed resulting in a drastic decrease of the false alarm rate.

At the moment three multi-sensor hand-held systems for landmine detection are operational: CyTerra AN/PSS-14, Minehound and ALIS [6]. All three systems include both metal detector and GPR. Numerous field trials have demonstrated considerable advantage of these systems over conventional metal detectors.

4.2 Luna Survey

Apollo Lunar Sounder Experiment by Apollo 17 was the first mission of space-borne GPR systems, and currently 3 systems, namely MARSIS, SHARD and Luna Sounder are in operation. Japan Aerospace Exploration Agency launched Lunar survey satellite SELENE in 2007[10]. SELENE is equipped with Lunar Radar Sounder, which is a low frequency GPR. This is a FM-CW radar operating at 4-6 MHz, and initial tests showed that it can observe the Luna subsurface up to 0.5-1.0km. This is an example of extremely low frequency GPR systems, but similar types of GPR at VHF range can be mounted on aircraft, and are used for ice thickness survey and geological survey.

5. Conclusion

Being the first commercial application of UWB radars GPR technology has matured since its introduction in 1974. Due to rapid development of both GPR hardware and software, its possibilities have been considerably extended resulting in widening the area of its applications. The major technological innovations in GPR are imaging, near-field polarimetry and digital array focusing. These innovations allow for detection of small objects and classification of detected targets. Even for well established applications newly developed technology allows for faster data acquisition and better discrimination of buried objects from subsurface clutter.

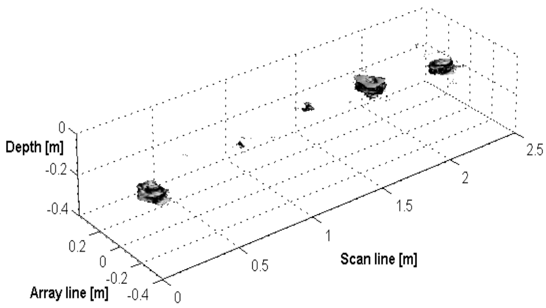

Figure 1 3D GPR image of buried antipersonnel landmines

Figure 2 ALIS in Operation

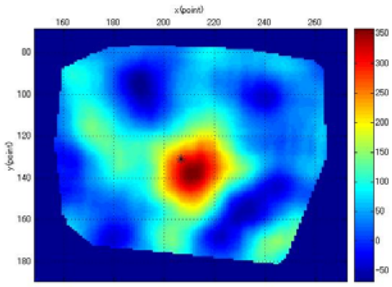

Figure 3 ALIS GPR image

6. Acknowledgments

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