INTRODUCTION OF A GROUND PENETRATING RADAR SYSTEM FOR INVESTIGATIONS ON CONCRETE STRUCTURES

VORSTELLUNG EINES BODENRADARSYSTEMS FÜR UNTERSUCHUNGEN AN BETONBAUTEILEN

PRESENTATION D'UNE SYSTEME RADAR POUR LA RECHERCHE DES CONSTRUCTIONS EN BETON

Finck, Florian

SUMMARY

Today, Ground Penetrating Radar (GPR) is a wide spread method for the investigation of building ground and engineering structures. The method allows for a rapid scanning of even long profiles and after some standard data processing, results can be evaluated on-site. Shallow investigations can be performed with high resolution, but an increasing target depth is at cost of resolution because of the attenuation of high frequencies. This year, the Institute of Construction Materials acquired a GSSI SIR-2 GPR system. Antennas with a centre frequency of 500, 900 and 1600 MHz are well-suited for various applications in civil engineering. In the following, some basic principles, the radar system and first measurements are presented.

ZUSAMMENFASSUNG

Das Bodenradarverfahren wird heutzutage vielfach zur Untersuchung von Baugrund und verschiedenen Bauwerken eingesetzt. Mit dem Verfahren können in kurzer Zeit große Messprofile abgescannt werden und nach einer standardisierten Datenbearbeitung ist vor Ort eine Beurteilung möglich. Oberflächennahe Messungen können mit einer sehr hohen Auflösung durchgeführt werden, allerdings geht eine zunehmende Erkundungstiefe auf Grund der Dämpfung hochfrequenter elektromagnetischer Wellen auf Kosten der Auflösung. Das Institut für Werkstoffe im Bauwesen befindet sich seit Anfang diesen Jahres in Besitz eines Bodenradargerätes SIR-2 von GSSI. Die Antennen mit einer Mittenfrequenz von 500, 900 und 1600 MHz erlauben vielfältige Anwendungen im Bereich des Bauwesens. In diesem Beitrag werden einige Grundlagen, das Radarsystem und erste Messungen vorgestellt.

RESUME

La systeme radar aura aujourdhui utilise pour la recherche des batiments et de la terre. Avec ce procede il est possible de faire des grands mesurages vites et apres une exploitation standard des donnees une evaluation est possible sur place. On peut faire des mesurages pres de la surface avec une resolution tres haute. Mais quand la profondeur d'exploration augmente a cause du assourdissement des ondes hautes frequences electromagnetiques la resolution descende. Depuis cette annee l'institut des materiaux pour le batiment possede une systeme radar SIR-2 de GSSI. Les antennes ont des frquences de 500, 900 et 1600 MHz. Elles permettent plusieurs utilisations en science des batiments. Dans ce article des principes basiques, la systeme radar et des mesurages auraient presente.

KEYWORDS: ground penetrating radar, concrete, resolution

1. INTRODUCTION

Ground Penetrating Radar (GPR) is a high resolution electromagnetic technique that is designed to investigate the shallow subsurface of the earth, building materials, and roads and bridges. Target objects are buried pipes, cables and reinforcement, caverns, flaws and cracks, as well as ground water and moisture, etc. Resolution of GPR primarily is a function of antenna frequency and the dielectric constant of the medium. With standard equipment, a resolution of much better than 1 cm can be achieved. On the other hand, resolution is obtained at the cost of penetration depth, since attenuation of electromagnetic waves in common building materials is rather high and increasing with frequency. Usually, GPR is applied in reflection mode, which yields a cross section of the subsurface, where electromagnetic waves are scattered and reflected at the target objects. Depth and shape of the objects are calculated from the runtime of the reflected signals over a profile. Measurements can be performed in a rapid scanning mode and the combination of various B-scans produces pseudo 3D images of the subsurface. When the object is accessible from more than one side, investigations can be carried out also in transmission mode yielding a tomography. The theory and application of GPR technique is similar to the one of the seismic reflection method and programs for the data processing are commercially available.

2. BASIC PRINCIPLES

In the early 20th century, the reflection of electromagnetic waves on metallic and non-metallic surfaces was used to detect barriers and objects and to evaluate the distance. During the 2nd world war, ***Ra****dio* ***d****etection* ***a****nd* ***r****anging* (radar) technology was enhanced for military applications. After the war, radar became soon an important tool for navigation, weather forecasting, etc. Since the 1950th, radar waves were used to estimate the thickness of arctic ice masses and glaciers. From the 1970th, also the structure of the shallow subsurface was investigated and first ground penetrating radar systems were commercially available.

A basic radar system consists of a control unit, an impulse generator, one or two antennas for the transmission and the receiving of the signals and a memory. The impulse generator sends short electric pulses (~ 1 ns) to the antenna with a rate of 50 kHz or more. For each of these pulses, the transmitter radiates an electromagnetic wave into the subject. The propagation and reflection is ruled by the electro magnetic parameters of the medium, which is discussed further down. However, reflected electromagnetic waves are detected by the receiving antenna. The acquisition and digitalization of these very high frequency signals is performed using a trick (fig.1).

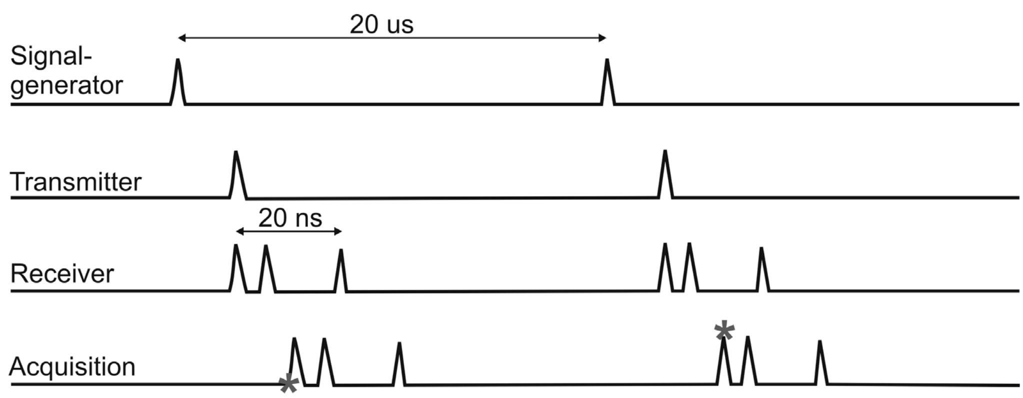

Fig.1: Scheme of step wise sampling a high frequency radar signal.

The trace of one point measurement is built by stringing together numerous single samples evaluated by the single impulses, which are sent with a rate of 50 KHz. The time delay between the samples is realized electronically. As an example, a point measurement with a trace of 512 samples needs approximately 0.01 seconds. This is fast enough to move the antenna over the profile and still achieve a good lateral resolution. In the single measurements, usually, the flash-over of the transmitter impulse and the reflection of the surface are inherent in the beginning of the trace. The reflections of the subsurface are following. Fig.2 represents an example of a single measurement.

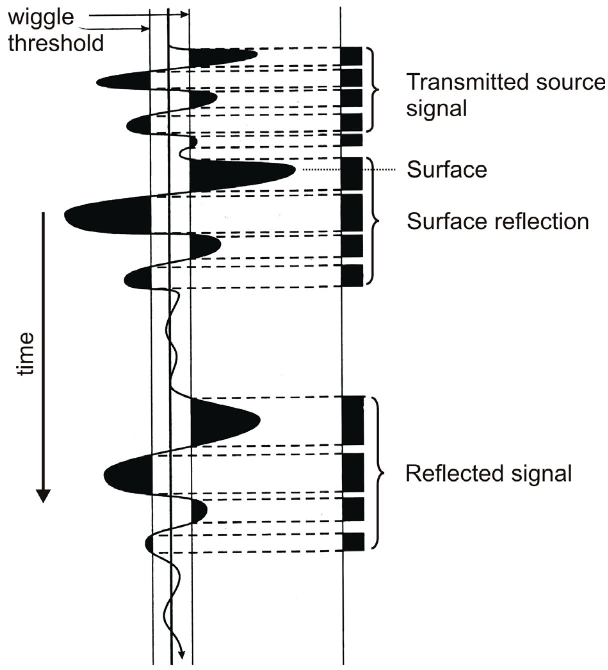

Fig.2: Example of a signal from a point measurement.

A sequence of single measurements then yields a B-scan, or radargramm. For the visualization, which can be plotted on-line, amplitudes exceeding a threshold are plotted in black (wiggle method), or the amplitudes are coded by a colour. The traces are stored in the memory of the control unit. The processing is performed after the measurement.

The physical principles of electromagnetic waves are based on Maxwell's equations [e.g. GERTHSEN AND VOGEL, 1993]. For the electric field **E** the formulation,

$$\Delta\mathbf{E} = \varepsilon\varepsilon_0\mu_0\ddot{\mathbf{E}} + \mu_0\sigma\dot{\mathbf{E}} \quad (1)$$

can be derived, where ε is the relative dielectricity and σ the conductivity of the medium. The formulation for the magnetic flux **B** is analogous. Eqn.1 is solved by the approach of an attenuated (δ) plane wave, propagating in x-direction. $k=\omega/c$ is the wave number, where ω is the angular frequency and c the vacuum velocity of light:

$$\mathbf{E} = \mathbf{E}_0\, \mathrm{e}^{i(\omega t - kx)}\, \mathrm{e}^{-\delta x}, \quad (2)$$

leading to the complex expression

$$(-\delta - \mathrm{i}k)^2 = -\mu_0 \varepsilon \varepsilon_0 \omega^2 + \mu_0 \sigma \mathrm{i} \omega \quad (3)$$

which can be decomposed into two real equations:

$$k^2 - \delta^2 = \mu_0 \varepsilon \varepsilon_0 \omega^2 \quad (4a)$$

$$2\delta k = \mu_0 \sigma \omega \quad (4b)$$

The first equation is the displacement term, governing at very high frequencies, and the second the conduction term, which is prominent at low frequencies. The frequency spectrum of GPR waves lies in between 10 MHz and 2.5 GHz and both terms have to be taken into account [e.g. DANIELS, 1996; REYNOLDS, 1997].

With the velocity v of the waves in the medium

$$v = c/\sqrt{\varepsilon} \quad (5)$$

refraction of electromagnetic waves is formulated by Snell's law:

$$\frac{\sin \alpha_1}{v_1} = \frac{\sin \alpha_2}{v_2} \quad (6)$$

Electromagnetic waves are also reflected on material boundaries and inhomogeneities. For high frequencies and a normal incidence, reflectivity R is only dependent on the relative dielectricities of the media:

$$R = \frac{\sqrt{\varepsilon_2} - \sqrt{\varepsilon_1}}{\sqrt{\varepsilon_2} + \sqrt{\varepsilon_1}} \quad (7)$$

Typically, reflections of inhomogeneities occur in the shape of hyperbola. The runtimes t_r for electromagnetic waves can be calculated by

$$t_r = 1/v \sqrt{x^2 + 4h^2} \quad (8)$$

where x is the lateral offset and h the depth.

Attenuation δ of electromagnetic waves is given by

$$(9) \quad \delta = \omega \sqrt{\left(\frac{\mu_0 \varepsilon \varepsilon_0}{2}\right)\left(\sqrt{1 + \frac{\sigma^2}{\omega^2 (\varepsilon \varepsilon_0)^2}} - 1\right)}.$$

With eqn.9, the skin depth $\Delta=1/\delta$ can be calculated, where the electromagnetic field has decayed with 1/e. This parameter is often used to describe the investigation depth.

An important role plays the resolution of the electromagnetic waves. As a rule of thumb, the Rayleigh resolution limit is defined by $\lambda/4$, where λ is the wave length. Of course the signal to noise ratio also governs the significance of the measurements and various processing tools and filters are available.

3. RADAR SYSTEM SIR-2

The SIR-2 GPR System, distributed by Geophysical Survey Systems Inc. (GSSI), was one of the most popular radar systems in the 1990's. It is very robust and user friendly and can be adapted to numerous applications. SIR-2 runs under a DOS operating system. In fig.3, the SIR-2 control unit is presented (down left) with the power supply and an IDS (Ingegneria Dei Sistemi S.p.A., Italy) 1.6 GHz antenna with survey wheel for high resolution investigations.

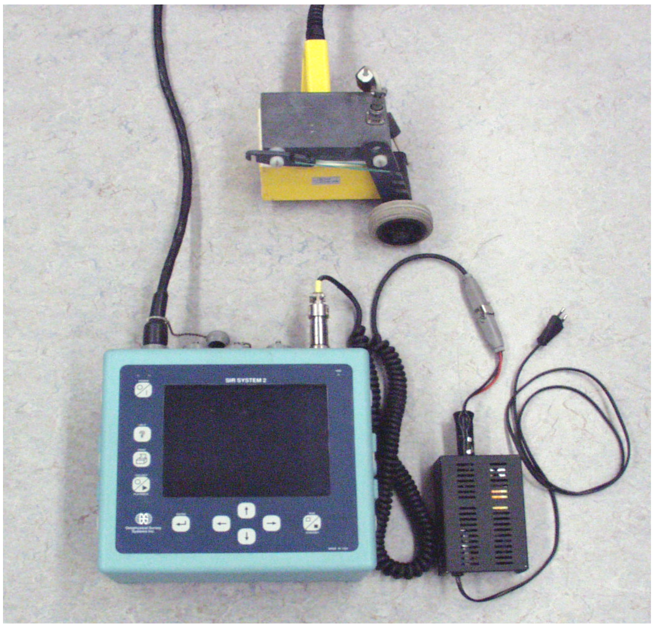

Fig.3: Control unit SIR-2 with power supply and 1.6 GHz antenna by IDS.

A 500 MHz antenna with handle bar and a 900 MHz antenna are presented in fig.4. A frame with a survey wheel will soon be developed for these antennas as well.

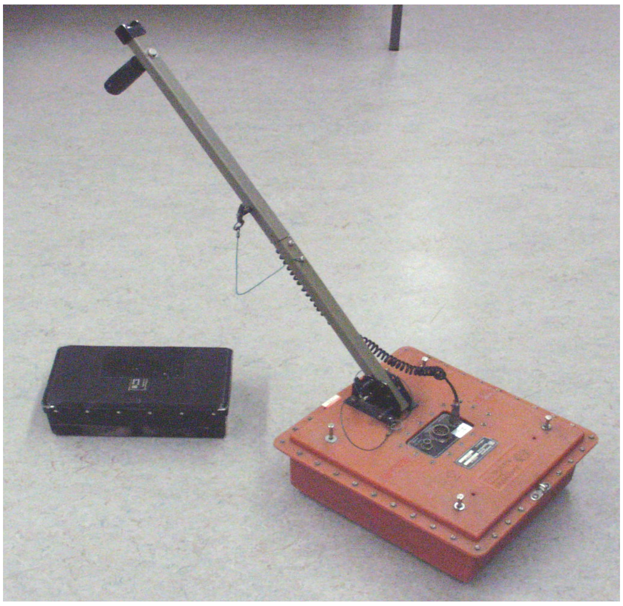

Fig.4: 500 MHz antenna with handle bar and 900 MHz antenna (both by GSSI).

The system requires a voltage of 12 V with 3 A, which can be provided by a car battery in the field or by an adaptor via the net.

In the set-up menu all parameters about the antennas, known material constants and the measuring procedure are defined. The measurements can be triggered manually, or better by the survey wheel. The latter provides equidistant scans along the profile. The collected data is plotted on the display on-line, and saved on a hard drive. By that, a first evaluation of the results can be performed on-site. After the measurements, the data is transferred to a personal computer via a serial data bus [SIR SYSTEM-2, Operation Manual, 1996].

For the final processing of the data, the software packet ReflexW by SANDMEIER [2002] offers a lot of options. The data can be filtered and migrated, to reduce geometrical effects and enhance the significance of the results. Pseudo 3D images can be generated for suitable data sets.

4. EXAMPLE OF MEASUREMENTS

Investigations were performed on a cascaded specimen (fig.5) with faults in various depths. This specimen was built for ultra sonic and impact echo measurements [Ruck and Beutel, 2001]. Geometrical effects of the numerous edges of the specimen caused problems in ultra sonic investigations. One profile ran over the center of the specimen, starting on the shallow step towards the deepest step. The measures of the specimen are given in fig.5, where *d* is the thickness of the various steps and *t* the depth of the faults in cm, respectively.

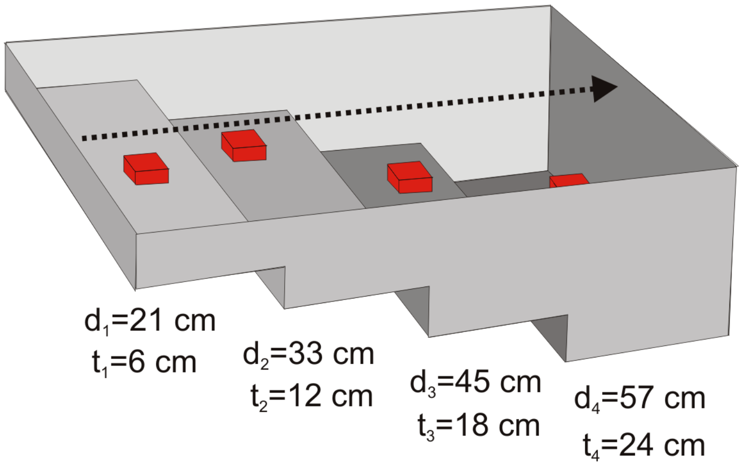

Fig.5: Cascaded specimen with faults in various depths.

Results of these investigations are presented in fig.6 and 7. The pseudo depth axis on the right is adapted to the measured data via a calibration measurement on the specimen, which revealed a electromagnetic wave velocity of approximately 0.1 m/ns, or an ε_r=9.

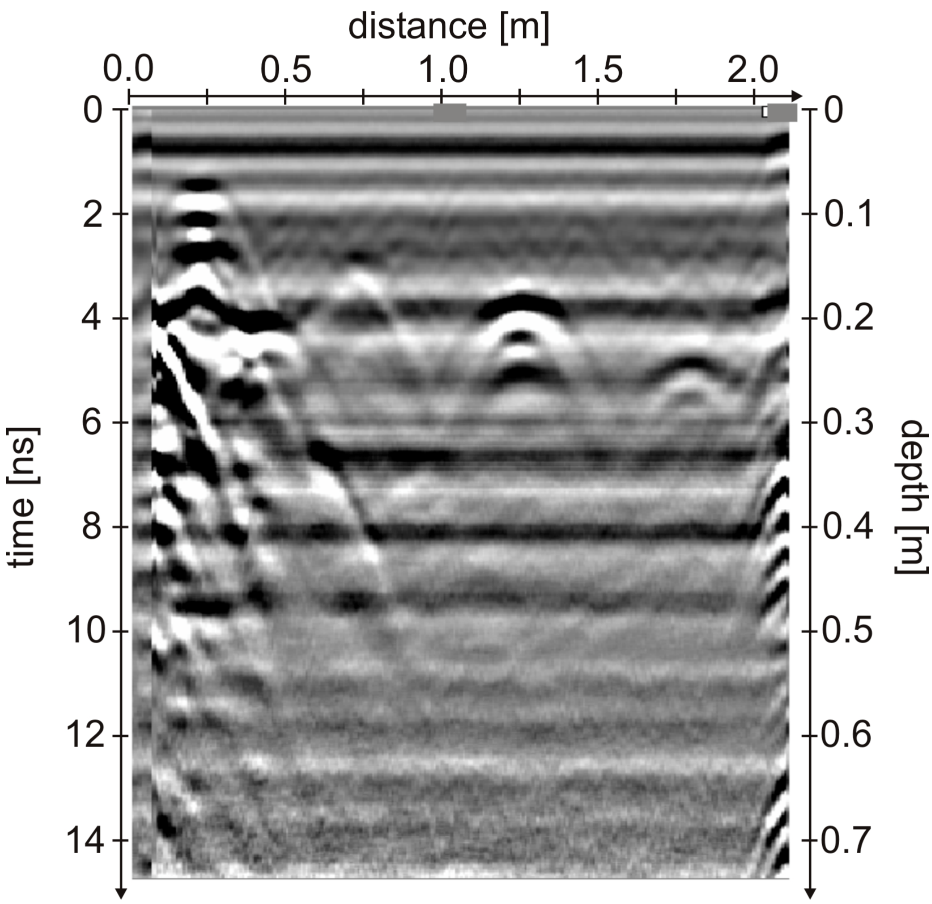

Fig.6: Raw GPR data of the central profile

The raw data in fig.6 show four prominent reflection hyperbola, representing the faults. The second reflection (from the left) is weaker than the others and appears slightly under the connecting line of the other reflections. No information of the signals can be assigned to back wall reflections. The data from the shallowest step is relatively noisy. To enhance the quality of the image and its significance, a Kirchhoff-migration [e.g. CONYERS AND GOODMAN, 1997] was performed on the data. This migration corrects the data for geometrical side-effects. The prism shaped faults become clearer and the hyperbola vanish. Also the back wall reflections of the shallowest and the second step are clearly visible.

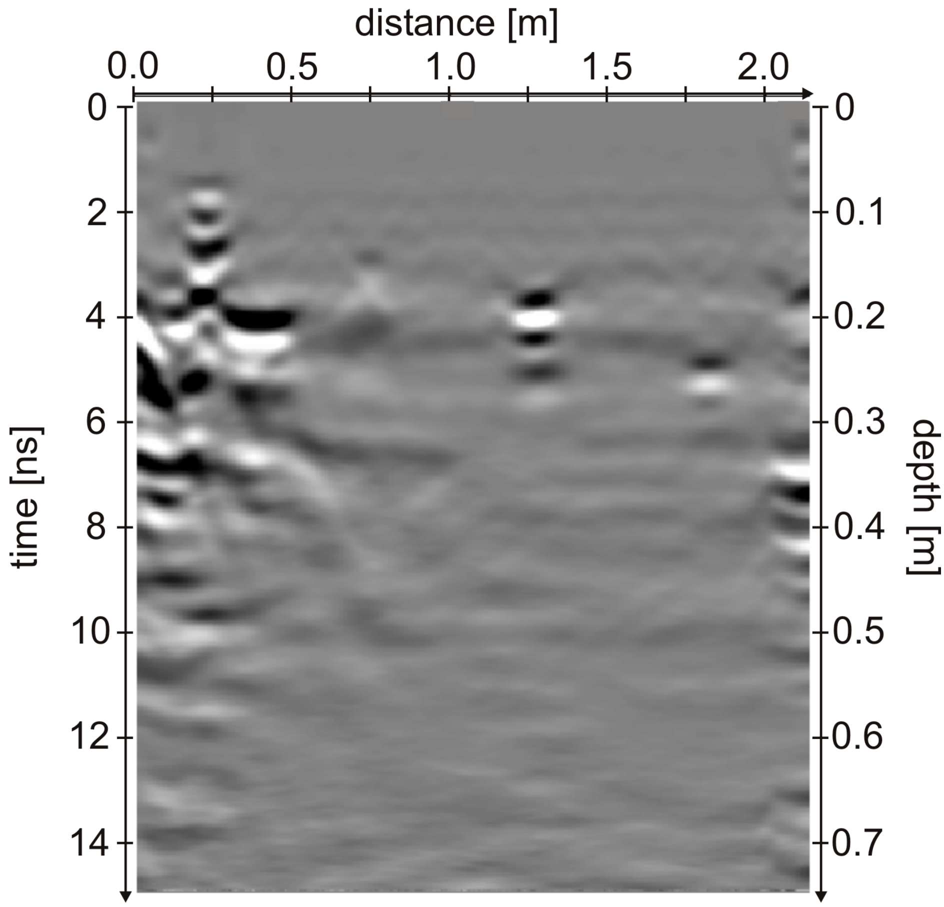

Fig.7: Migration of the section presented in fig.6.

The reflection of the fault in the second step is weak again. This fault is not placed in the center of the specimen, so the reflections, which are visible in the data, are generated by the side of the fault. This is also the reason, why this fault appears deeper than it is.

This example shows, that the radar system is very well-suited for high resolution investigations. After the migration, also geometrical effects can be minimized. The positions and depths of the reflectors do very well correlate with the real dimensions of the specimen. On the other hand, the limited depth of investigation is obvious. The back wall of the third step is expected in a depth of 45 cm, but there is no clear reflection, only a weak shadow. For these target depths, additional measurements with an antenna with a lower frequency would be necessary.

5. CONCLUSION

The SIR-2 GPR system allows for small and mid-sized investigations of concrete and stone constructions, building ground, tunnels, etc. The antennas with frequencies of 500, 900 and 1600 MHz offer a wide range of resolution and penetration depth. Within the frame of a diploma thesis, studies on the resolution of the system under varying conditions are performed.

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