A new direction-sensitive borehole logging tool for the spatial reconnaissance of geological structures

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Abstract - Spatial underground surveying from a single borehole is of great interest to cavern and mining engineers for economic and safety reasons. Direction-sensitive borehole ground penetrating radar (GPR) is a valuable technique which can be used for this purpose and has been successfully used in low conductive material in particular, such as salt and granite.

A new direction-sensitive antenna has been designed to improve the accuracy of direction location at the same time as increasing the sensitivity of the log. The new antenna compensates the eccentric position of the log in the borehole by using a special type of antenna. This increases the accuracy of direction determination. In addition, a combination of different loops and changing their polarity improves the signal/noise ratio and increases the dynamics of the receiving signals. The dynamics of the system are also increased by using a time-regulated amplifier. The concept behind this technique is illustrated in this paper alongside measurement examples.

***Keywords* – GPR, pulse radar, borehole logging, direction finding antenna.**

I. INTRODUCTION

An underground geophysical logging technique must be able to record and resolve information from the whole of the surrounding space so that the spatial position of structures and heterogeneities can be identified. GPR borehole measurements satisfy this criterion by using direction-sensitive receiving antennae.

GPR is an important tool in the geological exploration of underground waste disposal sites, because it is a non-destructive measuring technique and logistically simple and economical compared to other exploration methods.

II. LOGGING TECHNIQUE AND SPATIAL EVALUATION

GPR borehole surveys take place along a defined profile because they are restricted to the track of a borehole. Surveying involves running a fixed transmitter/receiver assembly along the profile in steps or continuously (Fig. 1). The technique involves extracting the spatial information from a survey along a linear one-dimensional alignment. GPR surveys are travel time surveys which enable distances to be determined if the velocity is known. If one assumes that a reflection horizon is located at an optically favorable position with regard to the survey profile, the travel time and velocity of each survey point can be used to determine the distance to a reflection point (Pn) on the reflecting horizon (Fig. 1)

The precise position within the reflection plane (the reflection plan is defined by the transmitter-receiver position and the reflection point) is determined using known migration techniques along the profile. In actual fact, this process not only involves determining the true distance, but also the angle λ (Fig. 1).

However, an angle and a distance are not enough to determine the precise position of a point in space, a second angle α at least is required.

This can be determined by using direction-sensitive receiving antennae. To incorporate the radial angle α recorded during surveying in the migration process, use is made of the wave front method [1], [3], [4], [6], [8] as applied in seismic processing. This is a robust method with the advantage that the measured receiving direction (α) can be incorporated in the migration process, and can still be applied even if the measurement point separations do not satisfy the Nyquist conditions.

Once the precise position of the reflection point has been determined, each of these points can be used to construct an elemental surface. Joining up the elemental surfaces of all of the reflection points generates a band in space which reveals the spatial position of the reflecting horizon. Because of the linear alignment and therefore rigid position of the transmitter-receiver arrangement compared to the reflection horizons, which in most cases are free-form surfaces, the optical conditions for receiving a reflection are often only satisfied over short sections of the profile. This means that only small patches of the reflection horizon are detected.

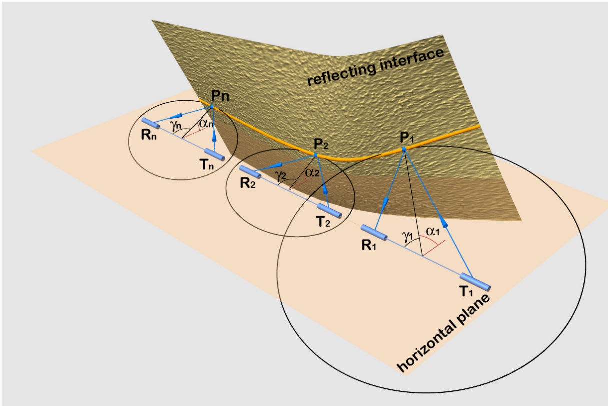

Figure 1. Principle behind determining the spatial position of a reflection point

The log therefore consists of a transmitter which send electromagnetic pulses into space omnidirectionally (Fig.2), and a receiving antenna capable of determining the receiving direction of every reflection. We have used a “cross loop antenna” as the direction-sensitive receiving antenna since the end of the 1980s: its general design is shown in Fig. 3.

The two loops can be switched together to form a dipole. The signals of the dipole and the two loop antennae are recorded at each logging point. The directional characteristic of a cross loop antenna corresponds to two eights rotated by 90° (Fig. 4). The direction angle α can be calculated using the formula (1) shown below. This involves recording the two loop signals via a time window which corresponds to approx. one wavelength, and assigning the value of the centre of this window. The angle is determined in this way for the whole track. Fig. 5 shows that this angle remains constant for a reflection if the reflection is error-free.

However, the directional characteristics of the loop antennae give rise to a 180° duality. This is resolved by dipole signals. If the dipole signal is in phase with the results calculated from the loop signals, (Fig. 5, b), then the angle is correct; if this is not the case (Fig. 5, a), then the correct answer is the angle plus 180°.

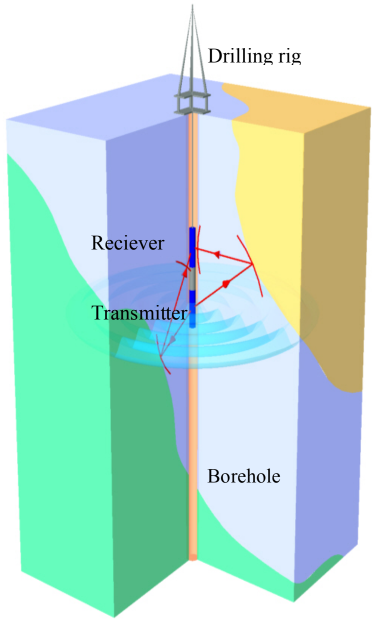

Figure. 2. Principle behind borehole GPR

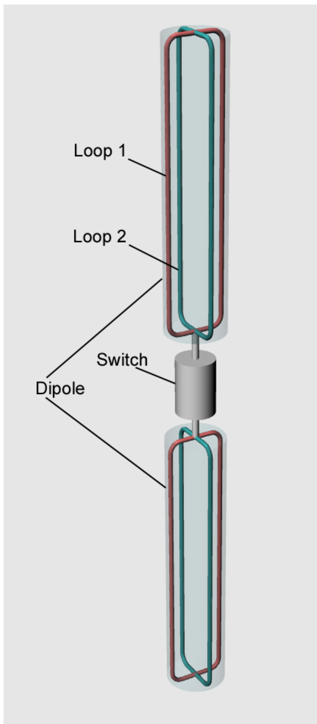

Figure 3. Direction-sensitive antenna (cross loop)

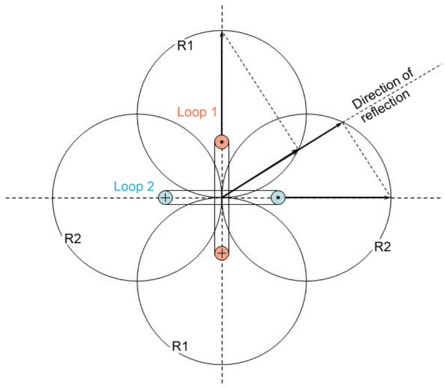

Figure 4. Characteristics pattern of a cross loop antenna

To be able to determine the absolute receiving direction of a reflection, it is also necessary to record the rotation angle of the probe. In vertical boreholes, the reference point is magnetic north and the rotation angle is determined using a compass. In the case of horizontal boreholes, the reference point chosen is a point vertically above the borehole, and the rotation angle is measured using a suitable angle transmitter.

$$\tan\alpha_{1,2} = \frac{1}{2\sum x_i y_i} \cdot \left[-\left(\sum x_i^2 - \sum y_i^2\right) \pm \sqrt{\left(\sum x_i^2 - \sum y_i^2\right)^2 + 4\left(\sum x_i y_i\right)^2}\right] \quad (1)$$

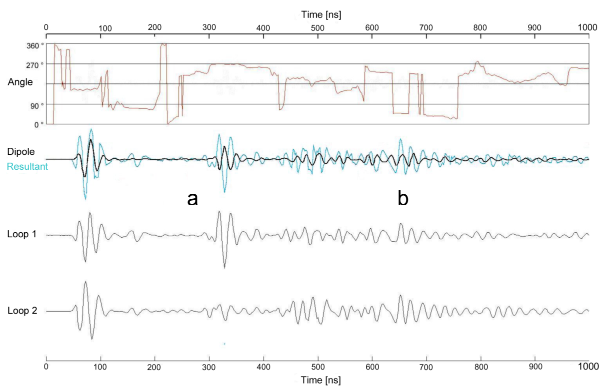

Figure 5. The three measured signals and the determined angle of the receiving direction

The receiving direction of a reflection is derived from the measured rotation angle and the calculated angle from the loop signals, Fig. 6.

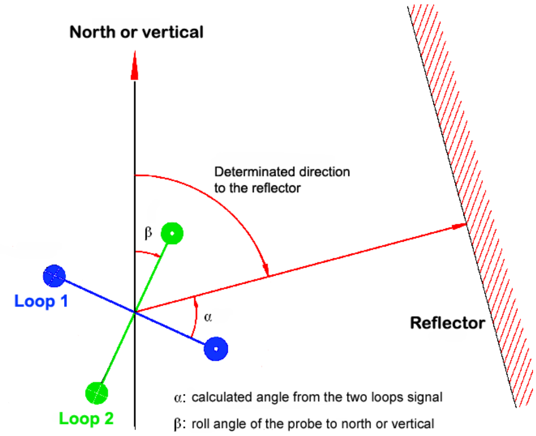

Figure 6. Determining the receiving direction of a reflection

BGR developed an evaluation system to spatially evaluate the borehole surveys. This evaluation system calculates the angle, migrates the spatial display, and visualises the reflectors it has determined. The reflectors are displayed as bands in space and submitted to the geologists as 3D information which can be used directly in a CAD graphic system to construct three-dimensional models.

The main advantage of the logging technique described above is that a single borehole can be used to acquire spatial information on the structure of the surrounding rock.

III. IMPROVING THE DIRECTION SENSITIVITY OF THE RECEIVING ANTENNAE

The diameter of a borehole can fluctuate significantly with respect to the diameter of the logging tool. This can cause the logging tool to lie eccentrically within the borehole, and thus give rise to an eccentric position of the antennae. This eccentricity affects the amplitude of the receiving signal recorded by classic loop antennae. Put simply, for the side of the logging tool which lies directly against the wall of the borehole, this means that the electromagnetic field strength is only dependent on the parameters of the adjacent rock, whilst the electromagnetic field strength on the other side of the logging tool also depends on the fluid in the borehole. This influence is shown schematically in Fig. 7. If we now use a twisted loop forming a type of butterfly antenna, and decouple the signal at the centre of the antenna, the eccentricity effects on the antenna become blurred (Fig. 8) and thus improves the directional determination of the reflections.

A new loop antenna with four twisted loops was constructed as shown in Fig. 10.

The antenna basically consists of two orthogonal loops A and B. These loops are coupled up to one another so that they enable four loop signals to be recorded (A+B+, A-B-, A+B-, A-B+). This coupling of the loops gives rise to an improved signal/noise ratio. The orthogonal loop antennae (A, B) are coupled up so that the reflection signal received at around 45° generates a maximum effective signal which is around 0.7 times the maximum of a single loop e.g. A+B+ = 0.7 (A+B-). In addition, the signals with inverse polarity are also recorded (A-B-). If the loop signals shifted by 180° are subtracted, this leads to the addition of the effective signals to give an effective signal around 1.4 times higher than an isolated loop signal, at the same time as reducing part of the noise signal (N) (which is constant, independent of the direction). The pattern of each loop coupling is shown in Fig. 9.

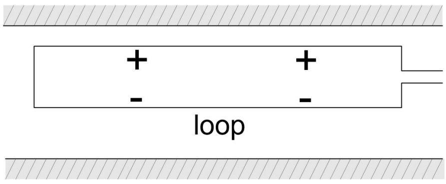

Figure 7. Eccentric position of a loop antenna in the borehole

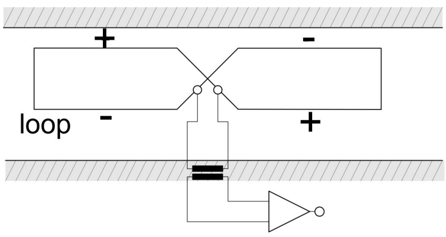

Figure 8. Eccentric position of a twisted loop antenna in a borehole

If the four possible alternative coupling positions are now measured and the counter-pole loop signals are subtracted, this gives rise to a new antenna pattern rotated by 45° boasting a higher effective signal (Fig. 9).

To cancel out the duality of a loop antenna, the dipole signal also has to be recorded. The loops are combined via transformers in such a way that it is also possible to measure a dipole signal.

A new borehole logging tool was constructed using this direction-sensitive receiving antenna, as shown in Fig. 11.

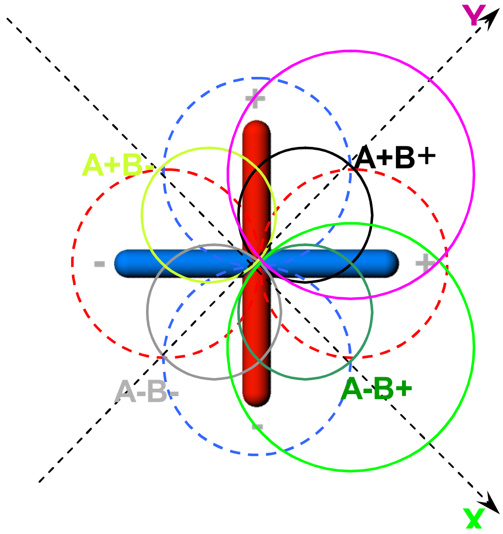

Figure 9. Pattern characteristics of the alternatively coupled loop antennae

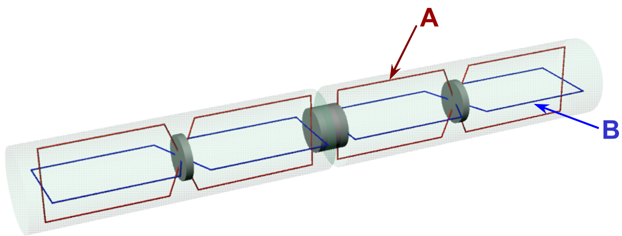

Figure 10. AT receiving antenna with twisted and alternatively coupled loop antennae

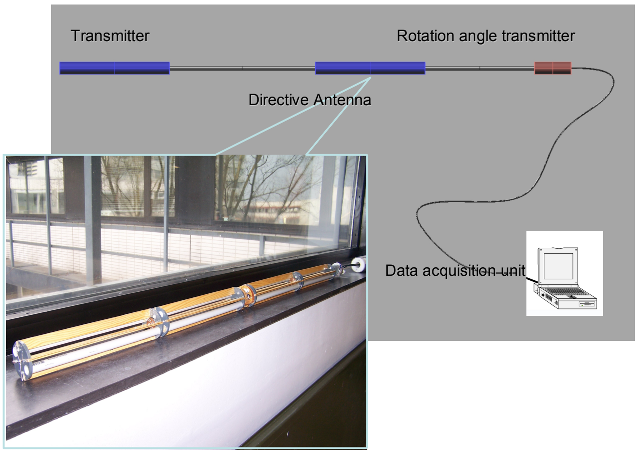

Figure 11. Direction-sensitive GPR borehole tool AT

The tool diameter is 80 mm and the centre frequency 50 MHz. Because of its lightweight construction it can be run into boreholes to a depth of 200 m by hand.

IV.TEST MEASUREMENTS TO VERIFY THE ANTENNA DESIGN OF THE TOOL

Test measurements were carried out in a test field in the salt mine Asse in North Germany to verify the directional characteristics and sensitivity of the logging tool (Fig. 12).

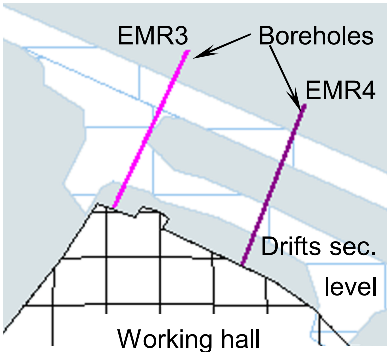

Figure 12. Test field in the salt mine Asse

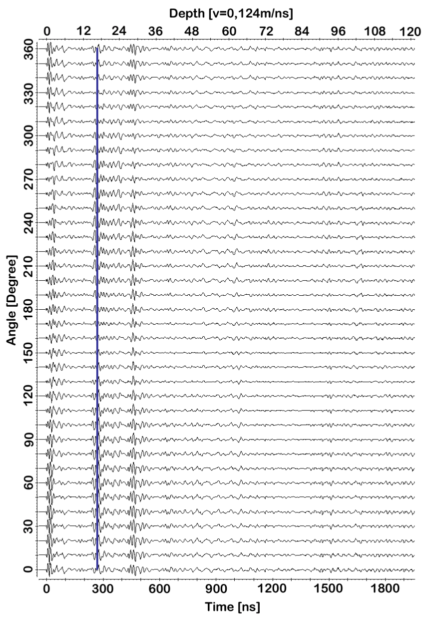

Figure 13. Radargram of the rotation test of the coupled loops A+B+

Two parallel boreholes separated by approx. 20 m were available, and were ideal to verify the directional characteristics of the receiving antenna. The receiving antenna was run into borehole EMR3, and the transmitter was run into

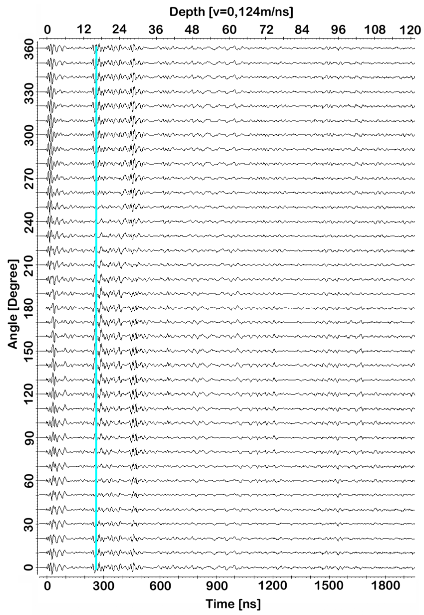

Figure 14. Radargram of the rotation test of the coupled loops A+B-

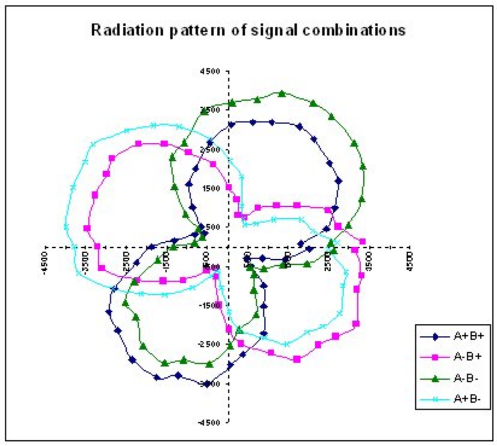

Figure 15. Directional diagram of the different loop combinations

borehole EMR4 to a depth of approx. 16 m. The receiving antenna was then rotated in 10° steps recording the 4 loop signals and the dipole signals. As expected, the dipole signal remained constant.

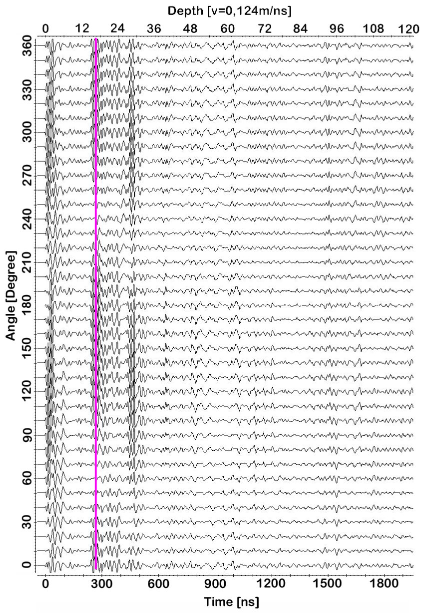

Figure 16. Radargram of the rotation test of the coupled loops A+B+ minus A-B-

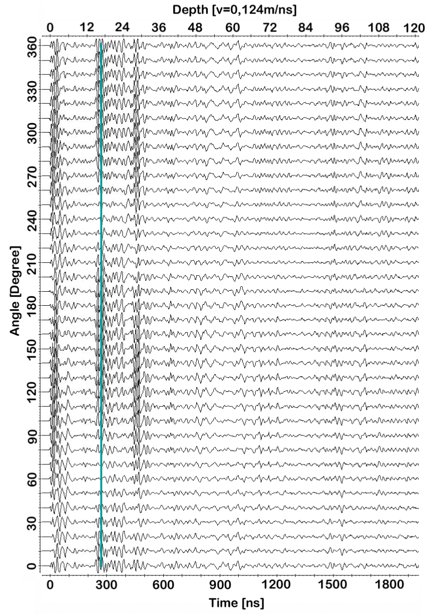

Figure 17. Radargram of the rotation test of the coupled loops A+B- minus A-B+

The signals from the different combinations and polarities of the loops also show, however, a clear angle dependency in Figures 13 to 14. The radargrams for the loop combinations A-B- and A-B+ looks like the combinations A+B+ and A+B- shifted with 90°. The angle dependency can be seen very clearly in the directional diagrams of each loop combination (Fig.15). If the reverse polarity loop combinations are subtracted (that means A+B+ minus A-B- and A+B- minus A-B+), the radargrams in Fig. 16 and Fig.17 show an improved effective signal. The directional diagrams in Fig. 18 show sharper minima which are attributable to lower noise. The effective signal/noise ratio was thus improved considerably.

If GPR surveys are planned in a borehole, care should be taken in advance when the borehole is being drilled. Boreholes drilled dry are the most suitable for radar surveys. However, because this is only possible for short boreholes, boreholes drilled using wet drilling methods have to be pumped out before surveying. If not alone water is used for the drilling mud, then it is also necessary to remove any mud cake remaining on the walls of the borehole. And if boreholes cannot be pumped dry for safety reasons, the drilling mud must be replaced by a non-conductive medium (e.g. oil). It is important that a borehole used for GPR logging does not contain any conducting materials.

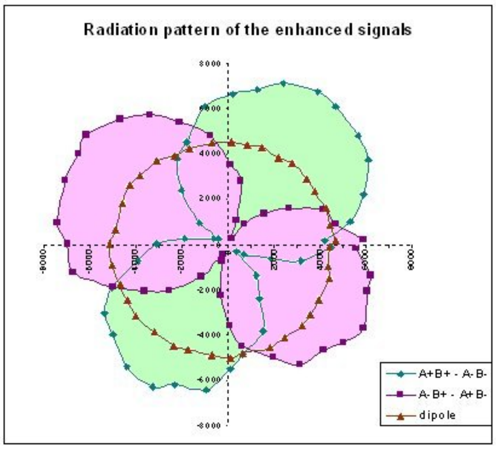

Figure 18. Directional diagram of the loops after subtraction

V. SUMMARY

The new direction-sensitive receiving antenna was developed to improve the direction sensitivity of the GPR logging tool. This new antenna consists of twisted loop antennae which can be combined in different ways. The advantage of this new antenna is that the eccentric position of the logging tool in the borehole can be partially compensated, and there is a clear improvement in the signal/noise ratio. The transmission tests carried out with a transmitter in one borehole and the new receiving antenna (AT) in another borehole 20 metres away, verified the symmetrical directional characteristics. The directional diagram revealed the improved signal/noise ratio (sharper zero crossings), and thus verifies the higher sensitivity of the antenna.

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