Principle of a direction sensitive borehole antenna with advanced technology and data examples

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***Abstract*—Underground, in mines it is important to get spatial information about the geology on limited profiles. In low conductive material, like salt, ground penetrating radar (GPR) is a valuable method to find structures in the environment. For radar measurements in boreholes a direction sensitive antenna can solve the problem of getting spatial information. A new development of a direction sensitive antenna with an advanced technology to calculate the direction increases the resolution of this method. The idea of this technique will be illustrated and examples of measurements are shown.**

***Index Terms*—borehole antenna; direction sensitive, GPR, salt.**

I. INTRODUCTION

GPR is a nondestructive method to get information about the spatial structure in a salt dome. The pulse radar emits an electromagnetic pulse from a dipole antenna into the rock and the returning signal contains reflections caused by differences in the electrical impedance of horizons. The travel time of the reflections contains the distance to structures. At measurements in drifts it is possible to get the direction of reflections by locating them with direction finding antennae [5].

In boreholes a direction sensitive borehole antenna with orthogonal loops is used. The ratio of the signal amplitude of these loops makes it possible to determine the direction at each point of the profile at each time in the signal. Such a logging tool was developed and built at the Federal Institute for Geosciences and Natural Resources more than 20 years ago [3]. For the exploration of salt mines this logging tool was rebuilt by the DMT (Deutsche Montan Technologie) complying with explosion proof conditions [2]. This borehole antenna was successful used for the exploration of salt mines. Results from measurements are described in [1]. Additionally a logging tool for cavern boreholes exists [4].

Now a new prototype of a direction sensitive borehole antenna with advanced technology is in progress.

This paper wants to explain the idea of the antenna and the differences to the previous logging tool. Data examples show the quality of the prototype.

II. PRINCIPLE OF THE DIRECTION SENSITIVE ANTENNA

A direction sensitive borehole logging tool consists of a transmitting dipole and two receiving cross loop antennae which can be switched as a dipole (Fig. 1). The signal of both loops and the dipole are measured at each point of a profile.

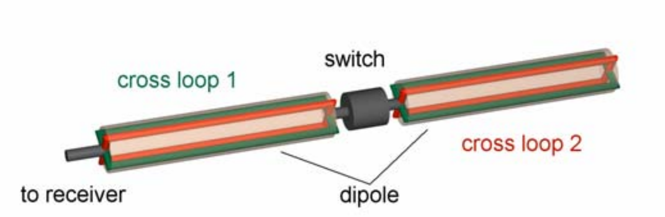

Fig. 1. Direction sensitive borehole antenna with orthogonal cross loops.

The angle α gives the direction of a signal relative to the reference direction β of the logging tool (Fig. 2). To obtain α the relation between the two cross loop antennae amplitudes (x, y) can be determined using a sliding window with the width of one wavelength:

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

The sign of the symmetric radiation pattern is determined using the dipole signal as a reference. The orientation of the logging tool β is determined with a compass with respect to north in a vertical borehole and with an angle of rotation sensor with respect to vertical in a horizontal borehole. Together α and β give an absolute value of the direction. A direction is assigned to each sample of the radar signal.

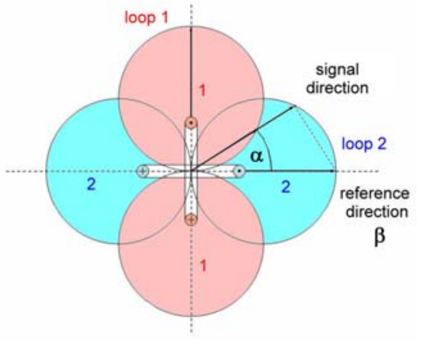

Fig. 2. Radiation pattern of the loops with direction angle to a reflected signal.

The assumption that is made for this estimation of signal directions is a symmetric radiation pattern. In general the influence of asymmetric parts in the signal is not very big. But there is an influence of the asymmetric position of the loop in a borehole what affects the loop signal (Fig. 3).

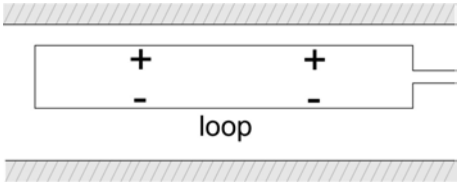

Fig. 3. Influence of the asymmetric position of the loop in a borehole.

A solution to this symmetry problem is a butterfly loop (Fig. 4). The signal of these loops contains the disturbances with different signs and can be eliminated.

The pickup of the signal is in the middle of the antenna and has to be done carefully.

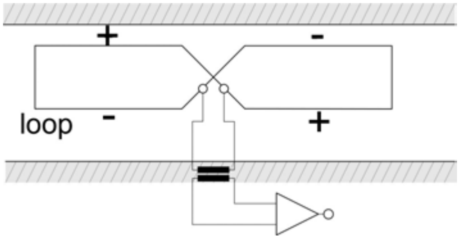

Fig. 4. Influence to a butterfly loop in an asymmetric position in a borehole.

To get an optimum of signal amplitude the different parts of the loop amplitudes are added or subtracted. The amplitude of a combined signal grows with the factor √2. The pattern of two combined parts is shown in Fig. 5. It is possible to combine four signals A_+B_+, A_+B_-, A_-B_- and A_-B_+ using a switch. These combined loop signals are distorted with 45° against the cross loops. This has to be regarded when calculating the rotation angle of a signal with respect to the loop.

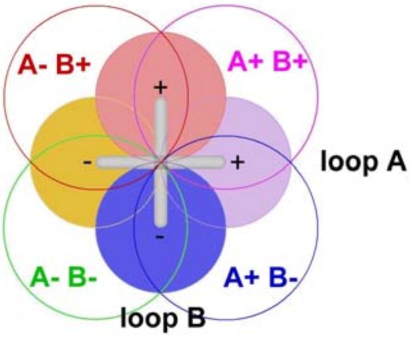

Fig. 5. Radiation pattern of the loops and the combination of two components.

By subtracting the faced signal combinations A_+B_+ - A_-B_- and A_+B_- - A_-B_+ the asymmetric parts of the radiation pattern disappear. With this enhanced and optimized loop signals it is possible to estimate the angle α refer to (1) together with the dipole signal the same way as described before.

III. Measurements with a prototype in a salt mine

A. *The test site*

The prototype was built in a light version for short boreholes (<200m). The dominant frequency of the antenna is 50 MHz. For a test of the attributes of the antenna a borehole in a salt mine was chosen. The borehole was drilled horizontal and is located nearly parallel to a drift. This makes it possible to place a transmitter into the drift and test the quality of the borehole antenna.

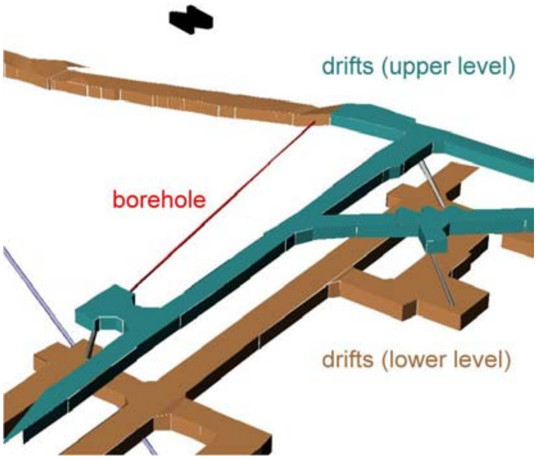

Fig. 6. Perspective view to the location of the borehole.

B. *Data from rotating the probe*

Measurements were made to verify the sensitivity of the antenna. Therefore the antenna was at a fixed position in the borehole and a transmitting dipole in a constant distance in the drift. Then the signals were recorded during a rotation of the probe from 360°.

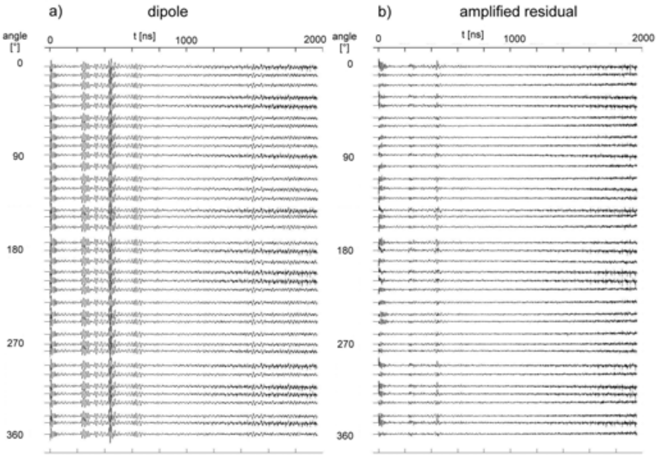

Fig. 7. Radargram from the dipole signal and its residual (amplified).

The dipole signal should have constant amplitudes independent from the rotation angle of the probe. This can be shown in the fig. 7 a). The diagram shows traces of 2 µs every 10°. More details of variations in the signal appear when the mean value of all traces is subtracted. The amplified traces in fig. 7 b) show only small variations at the reflections, but without relation to the rotation.

The results of the four different combinations of loop signals during the rotation of the probe are shown in fig. 8 and 9. The reflections in the diagrams reveal two clear minima and maxima during the rotation. In fig. 8 a) and 8 b) the signals contain the same reflecting structures, but with different phases. This applies to the signals in fig. 9 too. But these signals have their amplitude extremes 90° rotated to the signals in fig. 8.

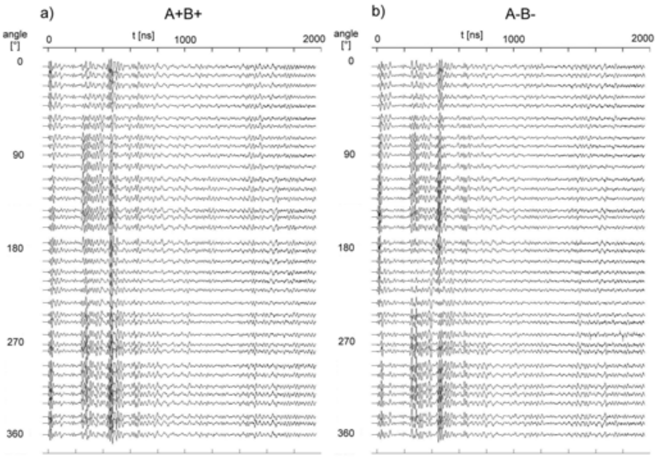

Fig. 8. Radargrams of the loop combination A_+B_+ and A_-B_-

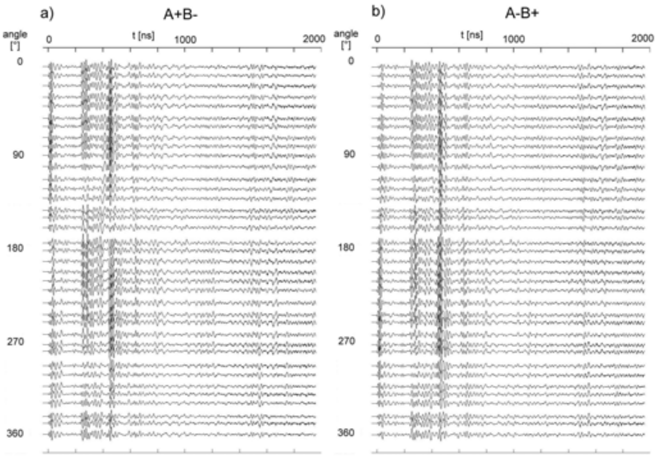

Fig. 9. Radargrams of the loop combination A_+B- and A_-B_+

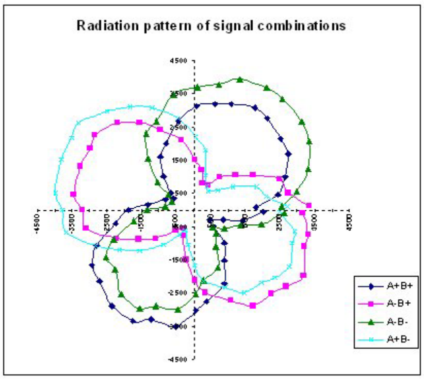

Fig. 10. Radiation pattern of the loop combinations.

The directivity of the antenna or the radiation pattern can be demonstrated clearly in a diagram with the signal amplitude of a reflection respect to the rotation angle. In fig. 10 you can see the pattern of all loop combinations for the reflection at travel time 253 ns. The variance in amplitude at each side represents the influence of asymmetric parts in the signal. Subtracting the signal combinations A_+B_+ - A_-B_- and A_+B_- - A_-B_+ the asymmetric parts of the signal are minimized. Fig. 11 shows the radargrams of these differences. The signal noise is reduced.

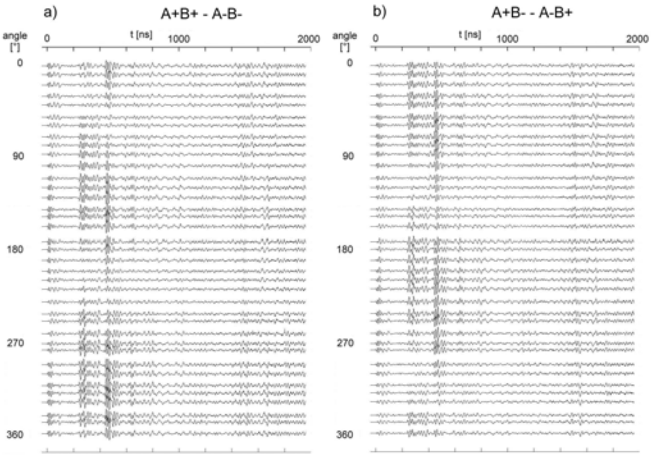

Fig. 11. Radargrams of the differences of the loop combinations.

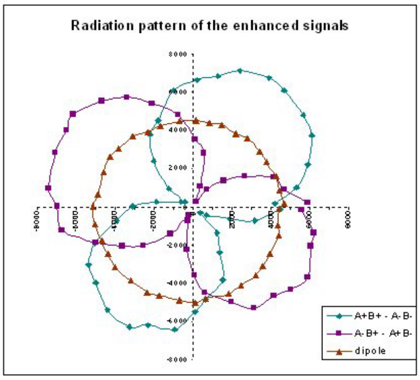

Fig. 12. Radiation pattern of the enhanced loop signals and the dipole.

Even now, after optimizing the signal, the shape of the eight is not completely symmetric, but the amplitudes of the maxima are higher and the minima are sharper as before (fig. 12). The dipole signal is constant. With these amplitudes it is possible to calculate the angle of a reflection at each rotation angle of the probe (fig. 13).

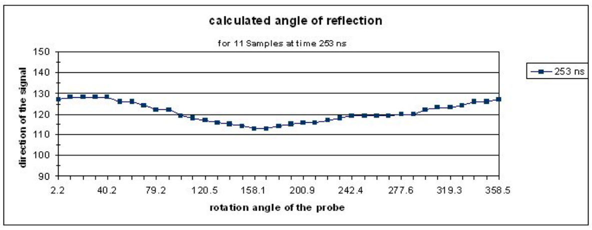

Fig. 13. Calculated angle of signal reflection while a rotation of the probe.

A symmetric directivity should result in a constant angle. The result for the angle of this reflection varies from 112° to 128°. The variation of ±8° of the estimated angle during a rotation of the probe is a remarkable result.

C. A profile in the borehole

The profile in the borehole was measured in steps of 1 m from depth 16 m to 32 m with a center frequency of 50 MHz. The separation of transmitter and receiving antenna was 8.5 m. The rotation of the probe along the profile leads to varying amplitudes of the loop signals (fig. 15, 16). The recorded time of the traces was 5 µs. Only up to 4 µs traces are displayed. With a wave velocity of 124 m/µs in salt this corresponds to a distance of 250 m.

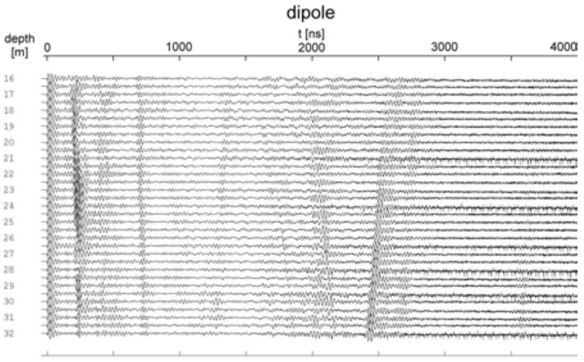

Fig. 14. Radargram of the dipole signal.

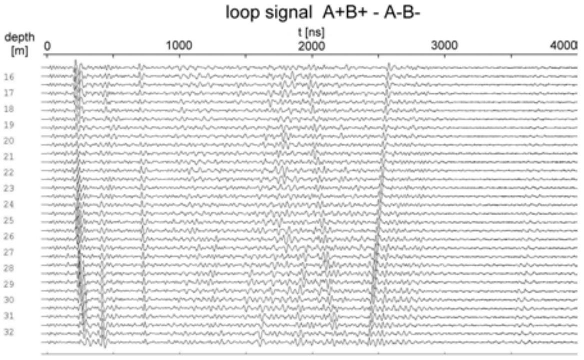

Fig. 15. Radargram of the loop signal $A_+B_+ - A_-B_-$.

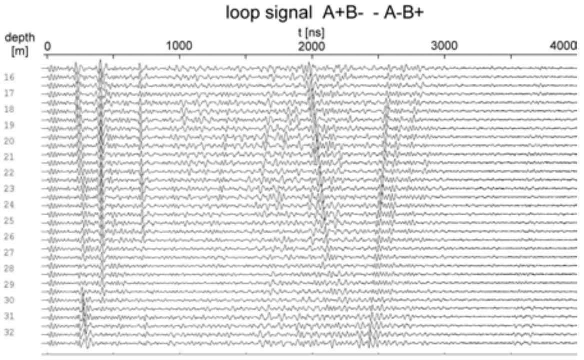

Fig. 16. Radargram of the loop signal $A_+B_- - A_-B_+$.

The profile of the dipole signal (fig. 14) shows reflections mainly from drifts. The reflection at 700 ns results from a geological structure. The loop signals (fig. 15, 16) have a low noise level compared to the dipole and show clear reflections. These signals were amplified during the measurements. This low signal/noise level leads to good results for the estimation of the direction of reflections.

The color coded diagram of the estimated angles (fig. 17) is scaled equidistant. It shows results for reflections up to a distance of 230 m.

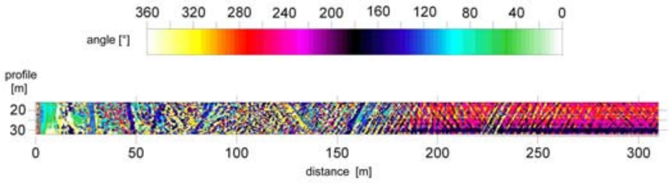

Fig. 17. Color coded diagram of the estimated angle from the profile in the borehole.

For this location the geological structure and the size of the drifts were known. The distances and directions of the reflections measured in this profile are correctly found at the right positions.

IV. CONCLUSION

The principle of direction sensitive borehole antennae can be optimized by using converted loops. This allows eliminating influences of asymmetric field components of the radar signal caused by coupling of the probe with the borehole. The result is a better estimation of the direction of reflections. The accurate spatial information about the structure in the environment of a borehole leads to valuable three dimensional geological models.

V. ACKNOWLEDGMENT

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