The direction sensitive borehole system DABoR and first results from a vertical borehole in salt

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***Abstract*—In low conductive material, like salt, ground penetrating radar (GPR) is a valuable method to get spatial information about the geology on limited profiles. For radar measurements in boreholes a direction sensitive antenna can solve the problem of getting spatial information. A development of an innovative direction sensitive, adaptive, borehole radar system (DABoR) with new electronic architecture increases the resolution of this method. The technique will be illustrated and an example of a measurement in a vertical borehole is 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] and a system with twisted loops to minimize borehole coupling effects [6].

Now a new direction sensitive borehole system with optimized electronics and adaptive antennae in cooperation with the University of Wuppertal and DMT is in progress [7, 8].

This paper wants to explain the advantages of the system and the differences to the previous logging tools. A data example from measurements in a vertical borehole in a salt dome shows the quality of the prototype.

II. STRUCTURE OF THE DABOR SYSTEM

First, tests were made and calculations were done to optimize the architecture and increase the efficiency of the direction sensitivity of the loop antenna. This was made for different frequencies, feeding point solutions and antenna geometries. The main result is the enhancement of the field pattern by opening the loop (compare Fig. 1, 2). At the open loop the shape of an eight is not only in equator plane, but also in pole plane.

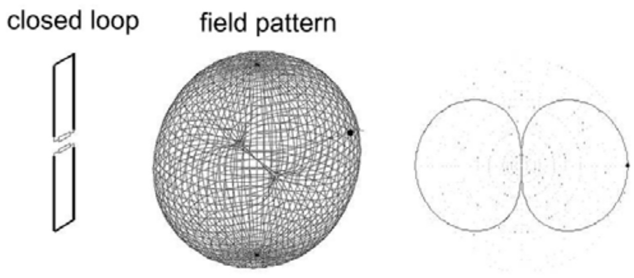

Fig. 1. Field pattern from a closed loop antenna.

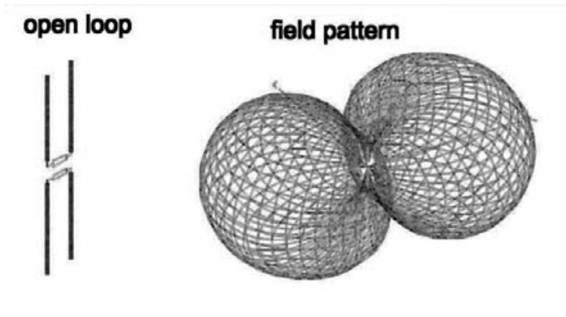

Fig. 2. Field pattern from an open loop antenna.

The DABoR system consists of several modules which makes it possible to transport the probe and handle it at heavy and narrow environments. The length of the modules is from 1.5 m to 2 m. The probe used for conducting the measurements has 50 MHz center frequency and a diameter of 100 mm. It is equipped with two orthogonally placed modified ‘loop’ antennas to achieve directional sensitivity [7, 8]. Active electronics at the antenna feed point does the amplification, digitalization of the received signals. The probe is capable of maximum 1 GSPS sampling rate and data stacking (averaging) of up to 1024 to enhance signal to noise ratio.

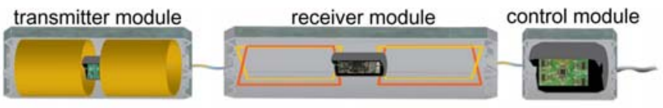

Fig. 3. Direction sensitive borehole probe with orthogonal cross loops.

The receiver module consists of a dipole and two cross loop antennae. Each antenna is connected to one input channel, which makes it possible to record all channels at the same time (Fig. 4). The antennae are connected to amplifiers with good clamping capabilities. Different gain stages can be selected by switches. The output of the amplification is connected to an Analog-Digital Converter. The data is stacked and stored by the data stacking block. The data stacking unit controls the interleaved sampling to get the best possible synchronization. The trigger signal is sent to the transmitter unit via fiber optics. A programmable microcontroller acquires voltages, temperature, condition of power supply, information from the orientation module and controls the measurement sequence.

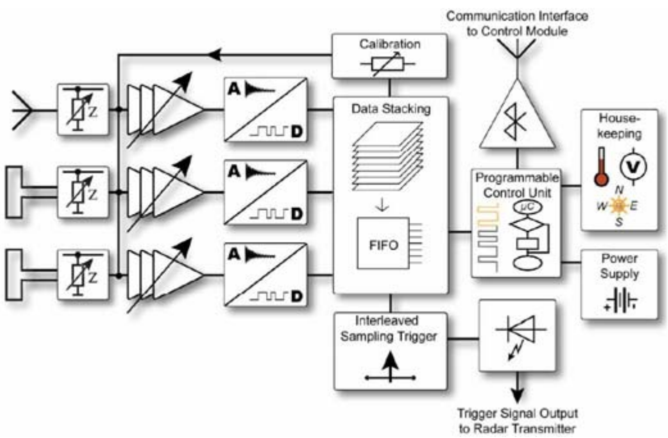

Fig. 4. Diagram from the receiver module [8].

The prototype of the DABoR system was built for boreholes up to a depth of 2000 m. The dominant frequency of the antenna is 50 MHz. With the data from the orientation module it is possible to reconstruct the borehole geometry.

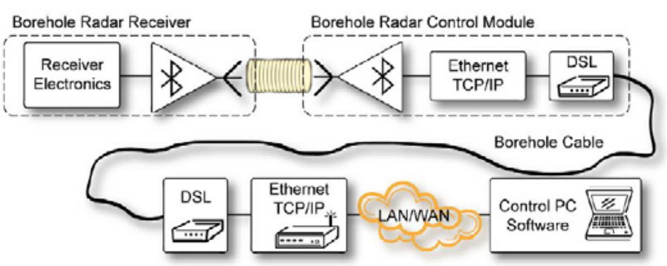

Fig. 5. Communication link to the acquisition computer [9].

The data acquisition computer is connected via Ethernet (TCP/IP) to a DSL modem (Fig. 5). This serial signal is transmitted via VDSL in the frequency range of ISDN over a borehole cable to the Control and Communication Module of the DABoR probe. The TCP/IP output of the DSL modem in the Control module is converted to RS232 and finally passed to a Bluetooth wireless module, which wirelessly links the module via waveguide of flexible length to the receiver module. A single fibre optic cable between the receiver module and the transmitter module is used for triggering the receiver and for transmitting status information like the battery voltage of the transmitter.

III. Principle of Getting the Direction

A direction sensitive borehole logging tool consists of a transmitting dipole and receiving cross loop antennae (yellow, orange) and a dipole (Fig. 3). The signal of both loops and the dipole are measured at each point of a profile.

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 magnetic field sensor with respect to north in a vertical borehole and with a gravimetric 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.

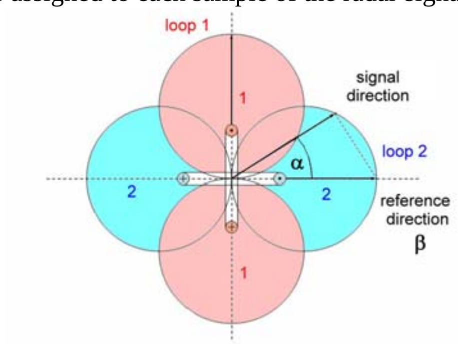

Fig. 6. Radiation pattern of the loops with direction angle to a reflected signal.

IV. Measurements in a Borehole in a Salt Mine

A. Directional response pattern of the receiving antenna

Measurements were made to verify the sensitivity and direction stability of the antenna. Therefore the antenna was placed at a fixed position in a horizontal borehole and a transmitting dipole in a constant distance in a parallel borehole. Then the signals were recorded during a 360° rotation of the probe. The signal of the dipole should be independent from the angle of the probe. The loop signals should have a 90° shift in amplitude maximum for each reflection. This is proofed by the diagrams in Figure 7-9. All the data was displayed with the same amplifying function.

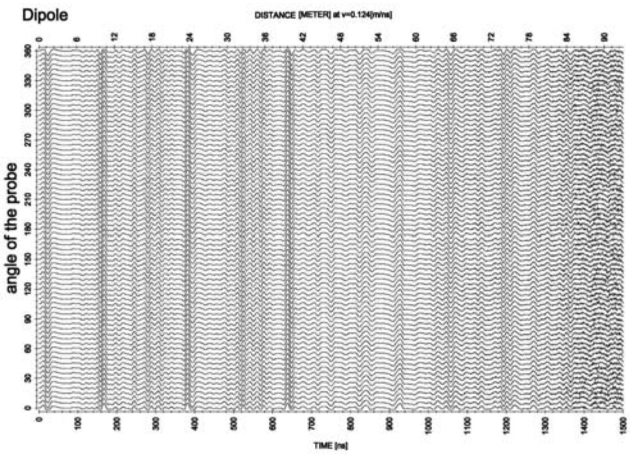

Fig. 7. Radargram from the dipole signal over one probe rotation.

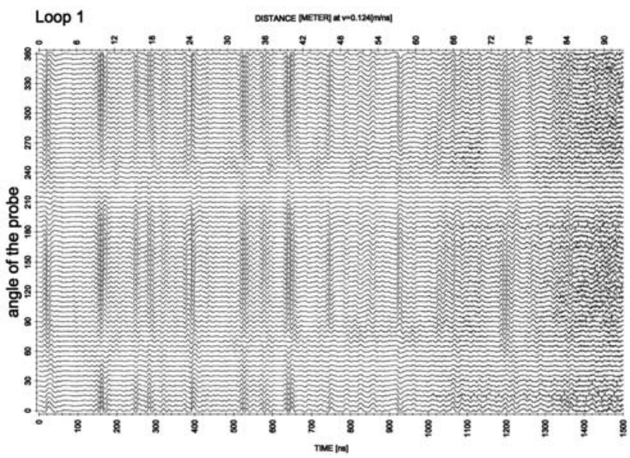

Fig. 8. Radargram from the traces of loop 1 over one probe rotation.

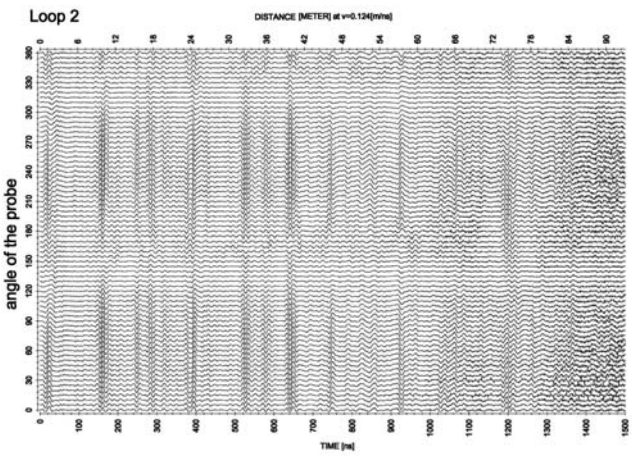

Fig. 9. Radargram from the traces of loop 2 over one probe rotation.

The low signal noise and excellent directivity can be shown by the radiation pattern from the dipole and loop signals at higher travel times. Even at 1198 ns the pattern shows a perfect circle for the dipole and an eight shape with sharp minima for the loops (Fig. 10).

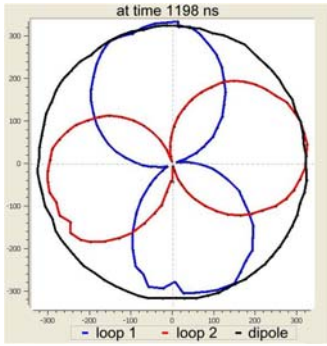

Fig. 10. Radiation pattern of the loop signals and the dipole at time 1198 ns.

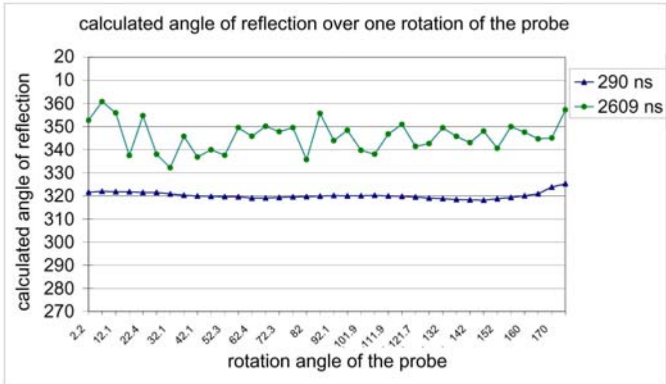

Fig. 11. Calculated angle of signal reflection while a rotation of the probe.

For the calculation of an angle of reflection the result should be constant if the rotation of the probe is taken into account. For two different times the angle over a half rotation of the probe is shown in Fig. 11. At short times (290 ns) the angle is constant within some degrees; at longer times (2609 ns) it is in a range of about ±10°.

B. The site

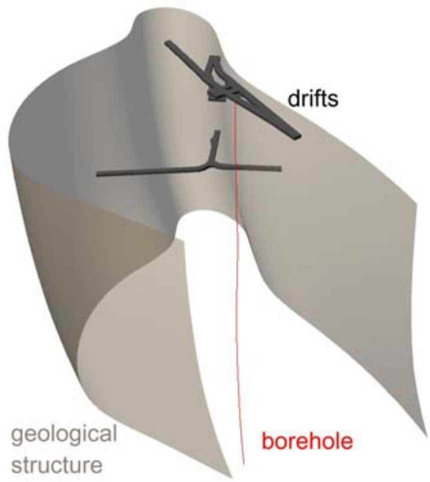

Fig. 12. Perspective view to the location of the borehole.

For the first application of the system a borehole in a salt mine was chosen. The borehole was drilled vertical more than

700 m starting in a drift and is located nearly parallel to a reflecting geological structure (Fig. 12). Some drifts at different depths of the profile, where the position of possible reflections is known, make it possible to improve the quality of the direction estimation. The extension and dip of the geological structure at both sides of the profile has to be investigated to plan further mining activities.

C. The radar profile in the borehole

The profile in the borehole was measured in steps of 1 m from depth 25 m to 50 m and again from 384 m to 655 m, in between the step width was extended to 1.5 m. The center frequency of the antenna was 50 MHz. The length of the whole probe was 15.8 m. The separation of transmitter and receiving antenna was 8.5 m. The probe was controlled by a half automatic winch.

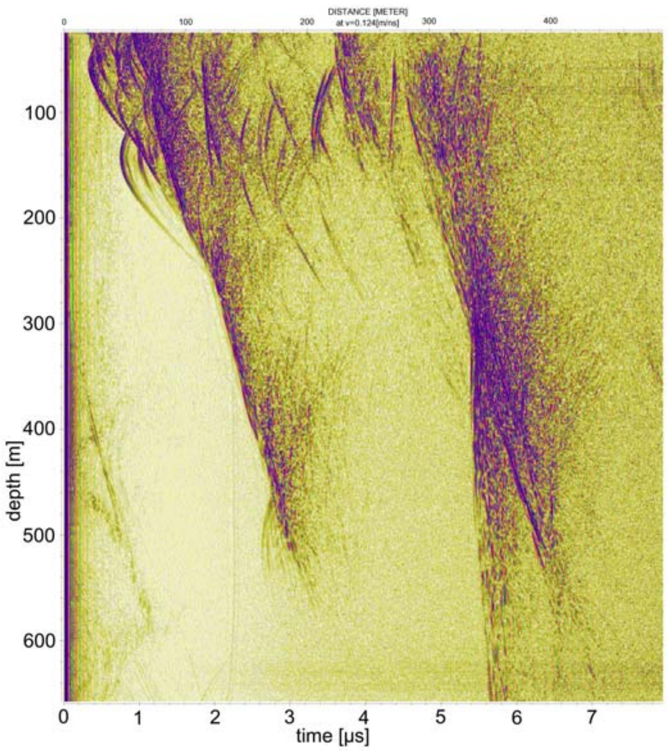

Fig. 13. Radargram of the dipole signal, color coded amplitudes.

The recorded time of the traces was 8.1 µs, 64-fold stacked. Only up to 7.8 µs traces are displayed. With a wave velocity of 124 m/µs in salt this corresponds to a distance of 480 m.

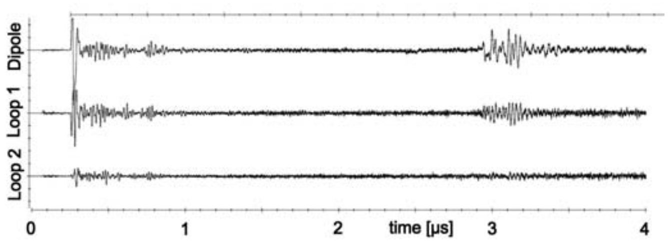

Fig. 14. Data example at depth 432 m, part of the traces, Dipole and loops.

To get an impression which traces are measured along the profile the dipole and loop signals are displayed in wiggle traces up to 4 µs at point 432 m (Fig. 14). After the pretrigger time the strong direct signal arrives. Due to the position of the probe the signal of loop 2 is weaker than loop 1. At 3 µs a strong reflection appears.

The profile of the dipole signal (fig. 13) shows in the upper part reflections from drifts mainly. Some of them occur as reflection hyperbolas. The strong reflection at 2 µs results from a shaft. Below depth 200 m two strong reflecting structures are dominant in a distance of 150 m and 350 m. The low signal/noise level leads to good results for the estimation of the direction of reflections and to a high penetration depth of the signal.

The color coded diagram of the estimated angles (fig. 15) is scaled equidistant. It shows results for reflections up to a distance of 400 m. The angle counts clockwise from North. So the main geological structures are found in Northeast (green) and in Southwest (violet).

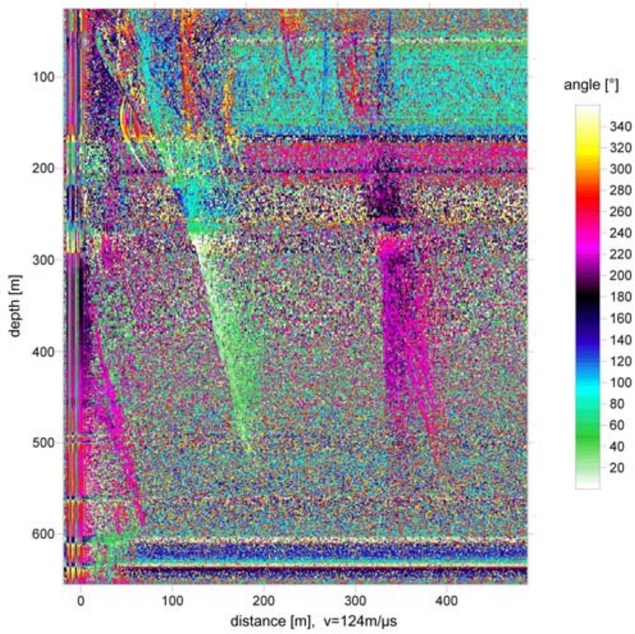

Fig. 15. Color coded diagram of the estimated angle from the profile in the borehole.

For this location the positions of the drifts but not the size and direction of the geological structure were known before. The distances and directions of the reflections from the drifts and shaft were found at the right positions (Fig. 16). This leads to a reliable model of the reflecting geological structure around the profile. The structures are reconstructed by migrating picked times of selected reflections taking the angle of reflection and borehole position of the probe into account. They are visualized by bands in space. These bands represent the reflecting geological horizons and are the basis for a 3D geological model.

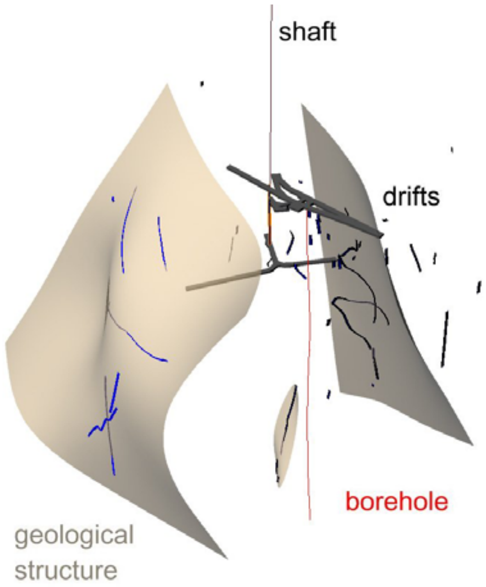

Fig. 16. Model of the structure around the borehole with radar results.

V. Conclusion

The direction sensitive borehole system DABoR was optimized in its electronic elements and the high frequency architecture. The result is a better estimation of the direction of reflections and a good signal/noise ratio. The accurate spatial information about the structure in the environment of a borehole leads to valuable three dimensional geological models.

VI. Acknowledgment

The development of this borehole system was supported by the Federal Ministry of Education and Research.

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