ACTIVE DIRECTION FINDING ANTENNA FOR BORE HOLES IN SALT DOMES

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Introduction
For the final deposit of nuclear waste salt mines are in common use. To prevent the underground water from nuclear contamination, however, it has to be verified that the salt mine in use is geophysically stable. Faults in the salt, often filled with a layer of wet clay, must not exist in the mining system and particularly not close to the nuclear material. For the detection of inhomogeneities in the salt a meterwave radar has been proposed /1/ which is in common use from inside of worked mines. For future use, however, unused salt domes are of particular interest. In this case a single bore hole is drilled to the salt dome from which the exploration has to take place. In the following an active direction finding antenna will be described which fits into bore holes of diameters down to 90mm and which can be used with the meterwave radar mentioned above.

Principle of the meterwave radar system
Fig. 1 shows a schematic drawing of the meterwave radar system in a bore hole. T is a battery powered transmitter which radiates bursts with a carrier frequency of about 60MHz via an omnidirectional dipole antenna. Incoming reflections from faults in the salt dome are received by the active direction finding antenna. From various simultaneous output signals of this receiving antenna the distance of the reflector and the angle of incidence of the reflected wave can be calculated. For this purpose the RF output signals of the receiving antenna are sampled and transmitted to the ground level via low frequency channels. The signals are stored on magnetic media for later computer processing. The computation of the distance of the reflector is easily performed by the measurement of the time delay of the echo compared to the transmitter signal. The problem to be described here is the determination of the angle of incidence.

Direction finding antenna
The passive part of the direction finding antenna inside a bore hole is shown in Fig. 2. It consists of two crossed loop antennas each of them providing two connection gaps. If the connections are loaded with high impedances, i.e. with high ohmic transistor amplifiers, the four output voltages fulfil the following conditions:

\[ v_{11} - v_{12} = \mu_0 A \cos \phi \frac{dH}{dt} \] (1)

\[ v_{21} - v_{22} = \mu_0 A \sin \phi \frac{dH}{dt} \] (2)

\[ v_{11} + v_{12} + v_{21} + v_{22} = 4 E_{\text{eff}} \sin \theta \] (3)

E and H are the instantaneous electric and magnetic field strengths, A is the area enclosed by each of the loops, and heff is the effective height of the passive antenna part. The angles of incidence, \( \phi \) and \( \theta \), can be seen from Fig. 2. Equations 1 and 2 describe the output voltages of the two crossed
loops, eqn. 3 describes the output voltage of an equivalent dipole antenna. To easily form the loop and dipole voltages as expressed in equations 1 through 3 high impedance differential amplifiers are used at each antenna gap which are shown in a basic schematic diagram in Fig. 3. The differential amplifiers have inverting and noninverting outputs. The respective output signals can be combined with the help of a network as shown in the block diagram of Fig. 4. The blocks signed "+" are simple resistor adding circuits. To eliminate the differentiation after time in equations 1 and 2 integrating amplifiers are used for the loop voltages. Fig. 5 shows a schematic diagram of an adding circuit and an integrating amplifier. \( R_1 \) are the adding resistors, \( C \) is the integrating capacitance, and \( T_1 \) is an amplifying transistor in base circuit. \( T_2 \) acts as a high impedance DC-current source for \( T_1 \), and \( T_3 \) is an impedance matching transistor with high input impedance.

In the following a plane echo wave, i.e. a far reflector is assumed. In this case, after the signal processing as shown in Fig. 4, the three simultaneously available output voltages can be written as

\[ v_E = 4 E_h \sin \theta \]  
(4)

\[ v_{H1} = \omega_o \mu_o A \frac{(E/Z)}{e} \cos \phi \]  
(5)

\[ v_{H2} = \omega_o \mu_o A \frac{(E/Z)}{e} \sin \phi \]  
(6)

where \( Z_e \) is the characteristic impedance of a plane wave in a medium with the dielectric constant of salt and \( \omega = \text{Ri}^* \text{C} \) is a factor caused by the adding and integrating networks (see Fig. 4). Fig. 6 shows examples for these three echo voltages after sampling. The obvious phase equality between the electrical and the magnetic voltages is a result of the integrating amplifiers.

By dividing \( v_{H1}/v_{H2} \), a value for \( \phi \) can be calculated. This value, however, is not unique due to the ambiguity of the tan function. This fact is well known from all crossed-loop direction finding antennas. As \( v_{H1} \) and \( v_{H2} \) are no continuous wave functions and will be disturbed by noise, an optimum estimation value for \( \phi \) can be calculated using the covariance functions

\[ \Gamma_{11} = \int_{t_1}^{t_1+\tau} v_{H1}^2 \, dt \quad \Gamma_{22} = \int_{t_1}^{t_1+\tau} v_{H2}^2 \, dt \quad \Gamma_{12} = \int_{t_1}^{t_1+\tau} v_{H1} v_{H2} \, dt \]  
(7)

The integration interval \( \tau \) begins at \( t_1 \), the beginning of the echo pulse, and includes the time with significant values of at least one of the voltages. With the notations of eqn. 7 one obtains

\[ \tan \phi = \frac{\Gamma_{12}}{\Gamma_{11}} \]  
(8)

or

\[ \cotan \phi = \frac{\Gamma_{12}}{\Gamma_{22}} \]  
(9)

From 8 and 9 that equation is chosen which shows the greater denominator. So far, \( \phi \) is still ambiguous. A unique value can be obtained with the help of the third output voltage \( v_E \). Denoting the additional covariance functions

\[ \Gamma_{EE} = \int_{t_1}^{t_1+\tau} v_E^2 \, dt \quad \Gamma_{1E} = \int_{t_1}^{t_1+\tau} v_E v_{H1} \, dt \quad \Gamma_{2E} = \int_{t_1}^{t_1+\tau} v_E v_{H2} \, dt \]  
(10)

for the vertical angle of incidence \( \theta \) one obtains
\[ \theta = \text{asin} \left\{ \frac{\Gamma_{1E} \sin \phi + \Gamma_{2E} \cos \phi}{\Gamma_{11} + \Gamma_{22} + (\Gamma_{11} - \Gamma_{22}) \cot \theta} \right\} \cdot \frac{\omega A}{c \cdot h_{\text{eff}}} \]  

(11)

where \( c \) is the phase velocity of a plane wave in the salt. In equ. 11 each of the two ambiguous results of either equation 8 or 9 can be used. The result of equ. 11 will show a change of 180° if the value of \( \phi \) is changed by 180°. Thus, using either value of equations 8 or 9 will guide to a unique horizontal angle of incidence, if \( \phi \) is used as calculated from equ. 11. Due to the ambiguity of the \( \text{asin} \) function only the angle \( \theta \) remains ambiguous for two values symmetrical to the horizontal plane \( \theta = 90^\circ \). This ambiguity, however, can be eliminated by series measurements along the depth of the bore hole.

Conclusion

A direction finding antenna for the frequency range of about 600MHz has been developed. It can be used in bore holes with diameters as small as 90mm in diameter. It consists of two crossed loop antennas with two feeder gaps each. With the help of high impedance transistor amplifiers additional to the loop voltages also an equivalent dipole voltage can be gained out of this structure. From these three simultaneously available output voltages a unique value of the horizontal angle of incidence can be determined. Only the vertical angle of incidence remains ambiguous for two symmetrical values. This ambiguity can be eliminated with series measurements.

References:


Fig. 1: Principle of a meter-wave exploration radar for bore holes in salt deposits.

Fig. 2: Passive antenna part and coordinate system for the incident wave.
Fig. 3: Differential antenna amplifier with high-impedance input and counter-phase outputs.

Fig. 4: Active network for the simultaneous combination of one dipole output voltage and two loop output voltages.

Fig. 5: Adding network and integrating amplifier.

Fig. 6: Sample output voltages for angles of incidence $\Phi=15^\circ$, $\Theta=90^\circ$. 

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