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Electromagnetic Technique for Locating Boreholes

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Electromagnetic Technique for Locating Boreholes

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UNITED STATES DEPARTMENT OF THE INTERIOR
Cecil D. Andrus, Secretary

BUREAU OF MINES

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ELECTROMAGNETIC TECHNIQUE FOR LOCATING BOREHOLES

by

H. Kenneth Sacks[1]

ABSTRACT

The Bureau of Mines has developed hardware for electromagnetic (EM) detection and location of miners trapped in underground coal mines. This report describes a technique for using the developed equipment for locating uncased boreholes underground. Results of several field and laboratory experiments are described.

INTRODUCTION

In many industrial situations, mining being a prime example, small-diameter holes are drilled from the surface to intersect an underground tunnel or room. The correct starting point on the surface is usually determined by standard surveying techniques. However, because of the tendency of small-diameter drill holes to drift, the true location of the bottom of a deep hole may be many feet from the expected coordinates. Often the true location will be determined by drilling small, horizontal pilot holes from within the underground opening in an effort to intersect the borehole. Depending on the diameter of the original borehole, the nature of the rock, and the luck of the driller, success may require considerable time and expense.

In previous work[2] a system was described for locating boreholes electromagnetically which depends upon a known receiver sensitivity and field strength. In practical situations, the field strength is a function of the electrical properties of the surrounding rock, which is generally unknown.

The technique to be described in this Bureau of Mines report eliminates this problem and it has proved to be accurate.

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[1] Supervisory electrical engineer, Pittsburgh Mining and Safety Research Center, Bureau of Mines, Pittsburgh, Pa.

[2] Tervo, R. L., and L. Tirrul. Lost a Borehole Recently. Can. Min. J., 1973, pp. 56-58.

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Acknowledgment is expressed to Harry Dobroski, Jr., and Carl W. Ganoe of the Pittsburgh Mining and Safety Research Center, Pittsburgh, Pa., for their assistance in building and carrying out the field tests.

TRAPPED MINER LOCATION EQUIPMENT

Under the Bureau's post disaster rescue and survival program, hardware was developed for detecting and locating miners trapped in underground coal mines. Experiments by the Bureau have shown the equipment to be effective in overburden depths up to 1,000 feet.

The hardware is shown in figures 1-2. Reports describing the equipment and techniques are available.[3] For purposes of this report, a brief functional description will be given. Figure 1 is the trapped miner transmitter. It is powered by the miner's cap lamp battery and when connected to a 90-ft-long, horizontal wire loop, it generates a 0.1-sec-duration tone burst of low frequency (630 to 3,030 Hz) current of about 5 amp root mean square (RMS) with a repetition rate of once per second. The tone-burst frequency is crystal controlled and fixed. Experimentation and theory has shown that signals lying

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[3]Collins Radio Group, Rockwell International. Waveform Generator for (EM) Location of Trapped Miners (Research Contract H0133045). BuMines Open File Rept. 9-75, 1974, 25 pp.; available from National Technical Information Service, Springfield, Va., PB 240 481/AS.

Farstad, A. J. Electromagnetic Location Experiments in a Deep Hardrock Mine (Research Contract H0242006). BuMines Open File Rept. 28-74, 1973, 54 pp.; available from National Technical Information Service, Springfield, Va., PB 232 808/AS.

Farstad, A. J., C. Fisher, R. F. Linfield, R. O. Maes, and B. Lindstrom. Trapped Miner Location and Communication System Development Program. Volume 1. Development and Testing of an Electromagnetic Location System (Research Contract H0220073). BuMines Open File Rept. 41(1)-74, 1973, 181 pp.; available from National Technical Information Service, Springfield, Va., PB 235 605/AS.

The preceding open file reports are available for consultation at the Bureau of Mines facilities in Denver, Colo., Twin Cities, Minn., Pittsburgh, Pa., and Spokane, Wash.; at the Department of Energy facility in Morgantown, W. Va.; and at the National Library of Natural Resources, U.S. Department of the Interior, Washington, D.C.

Powell, J. A. An Electromagnetic System for Detecting and Locating Trapped Miners. BuMines RI 8159, 1976, 15 pp.

Westinghouse Electric Corporation. Coal Mine Rescue and Survival. Volume 2. Communications/Location Subsystem. BuMines Open File Rept. 9(2)-72, 1972, 258 pp.; available for consultation at the Bureau of Mines facilities in Denver, Colo., Twin Cities, Minn., Pittsburgh, Pa., and Spokane, Wash.; at the Office of the Assistant Director--Mining, Columbia Plaza, Washington, D.C.; at the National Library of Natural Resources, U.S. Department of the Interior, Washington, D.C.; and from the National Technical Information Service, Springfield, Va., PB 208 267.

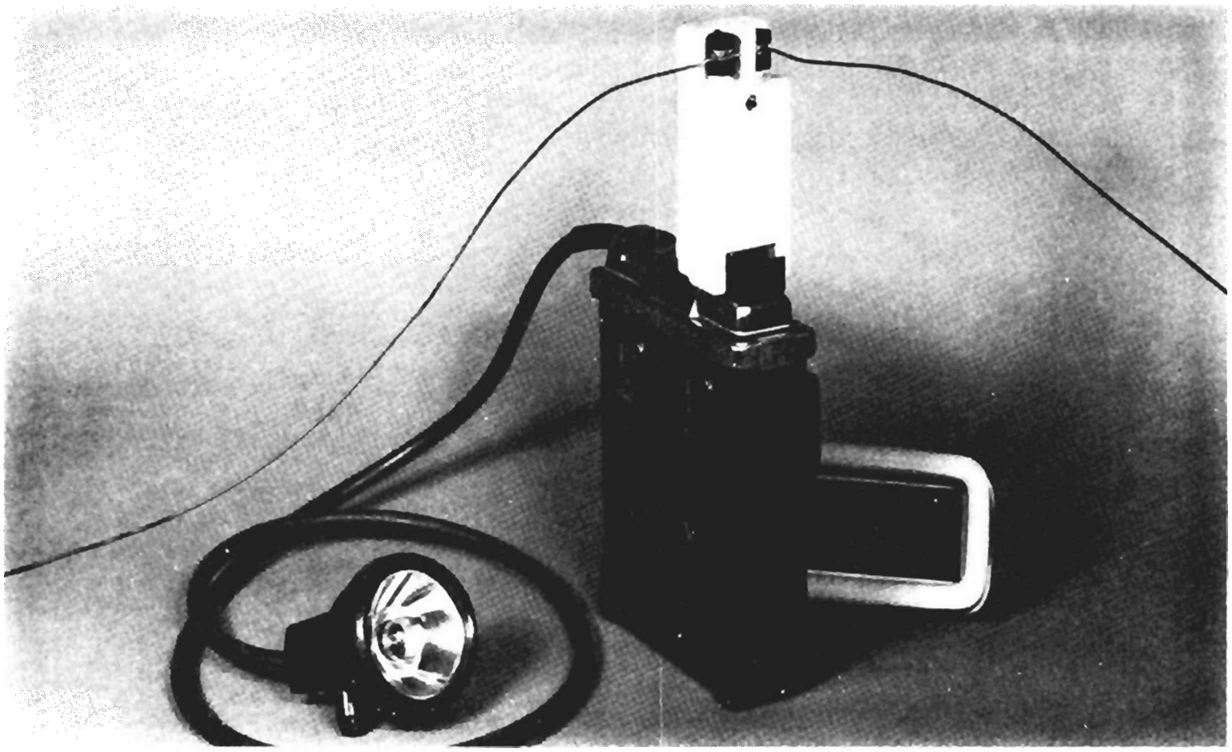

FIGURE 1. - Trapped miner transmitter.

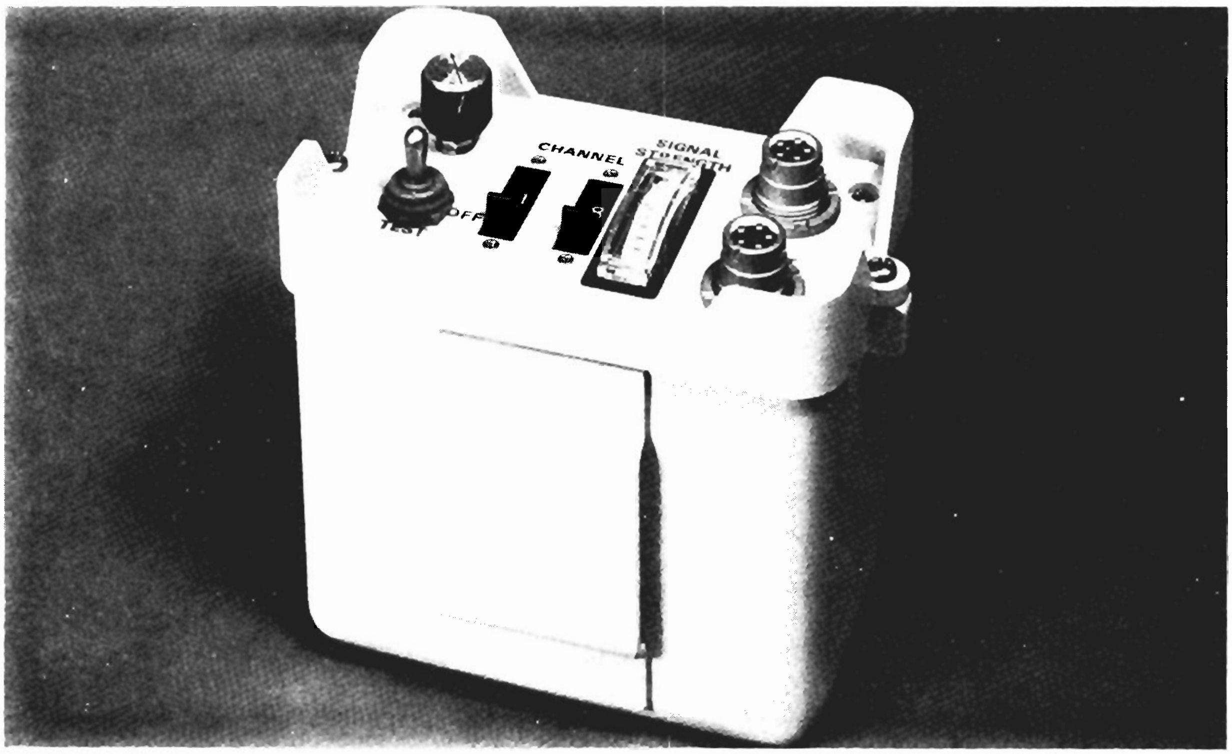

FIGURE 2. - Trapped miner receiver.

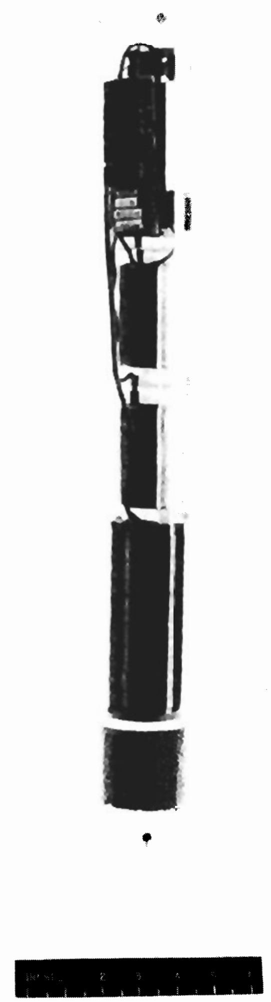

FIGURE 3. - Borehole transmitter.

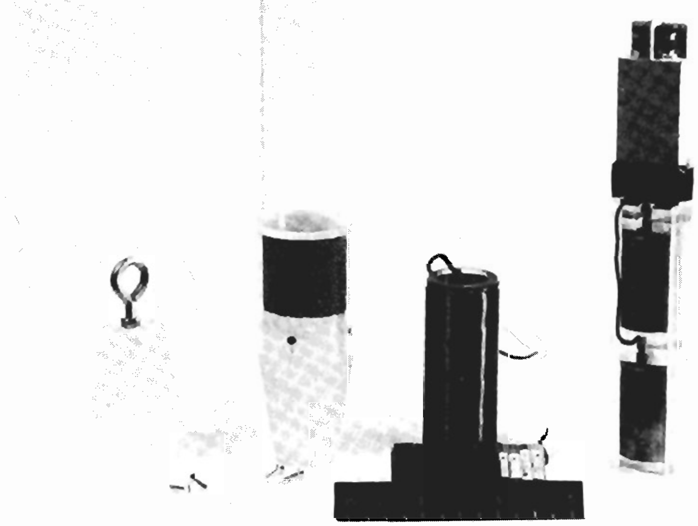

FIGURE 4. - Transmitter disassembled showing from left to right, top seal, plastic case, coil and tuning capacitors, transmitter module, and batteries.

in the low audio range (<2,000 Hz) propagate best through the earth. By spacing the tone-burst frequencies midway between the harmonics of 60 Hz (that is, 810, 870, 930, 990, 1,050, etc.) interference from powerlines is greatly reduced.

The current in the wire loop produces a magnetic field that can be detected at the surface with the receiver shown in figure 2. The receiver can tune to any one of the predetermined frequencies produced by the transmitters. Its channel bandwidth is 25 Hz and it has a sensitivity of better than 0.1 microamp/m at 1,000 Hz. The narrow bandwidth and high sensitivity allows weak signals to be detected in the presence of background noise. These two units form the basic components of the borehole location technique.

Transmitter

An uncased borehole, for the purpose of this report, is any hole without a metallic casing in the vicinity of the underground opening. Holes cased in concrete or holes with metal linings that do not extend down to the underground opening are considered uncased.

For the borehole location system, the transmitter of figure 1 was packaged in a 2-3/4-in-diam plastic container as shown in figures 3-4. A nonconducting material must be used for the container to prevent electromagnetic shielding which greatly reduces the received field. The coil is tuned to the tone-burst frequency. Appendix A gives the details for the coil design. To conserve battery power, the battery is connected to the transmitter and the package is sealed just before the unit is lowered into the borehole. The 10-pct duty cycle of the transmitter (0.1 sec on, 1 sec off) allows a battery life in excess of 20 hr.

Null Detection Technique

Figure 5 is a plan view of the transmitter lowered down the hole. The magnetic field lines from the transmitter coil are radial. When the plane of

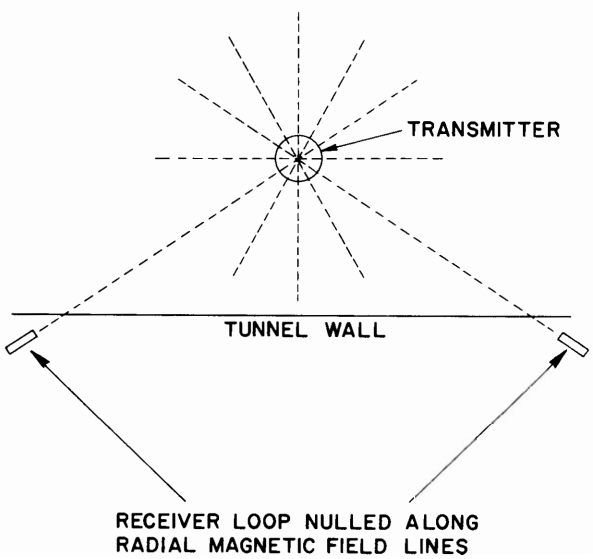

FIGURE 5. - Plan view of transmitter in borehole and tunnel.

FIGURE 6. - Receiver coil mounted on transit.

the receiver coil is vertical and alined with the radial field lines, the received signal is a minimum or "nulled." This signal null is generally very sharp; that is, a slight change in the receiver coil azimuth gives a large signal increase. If the receiver coil is moved to another spot along the tunnel and nulled again, the position of the borehole can be found by triangulation. To aid in this scheme, the receiver coil is mounted on a surveyor's transit (fig. 6) which allows precise measurement of the coil angle with respect to a reference line for use in determining the hole location.

It is important for the transmitter coil not to be at the tunnel level, because the magnetic field will then have only a vertical component at the receiver and the received signal will be at a minimum for all azimuthal orientations. If the distance into the rock to the transmitter were known, then an optimum height above or below the tunnel would be equal to this distance (see appendix B).

Field Test

In the fall of 1975, the U.S. Army Corps of Engineers requested the Bureau's aid in locating a 10-in-diam fresh water well in the vicinity of an underground tunnel at Ft. Ritchie, Md. The Bureau used the equipment and techniques just described to accomplish the task. Figure 7 shows the layout of the tunnel and field results. A 50-ft baseline was laid out along the tunnel and null measurements were taken at six positions. Multiple readings were taken to increase the confidence of the results. The shaded area represents the most likely area of the hole.

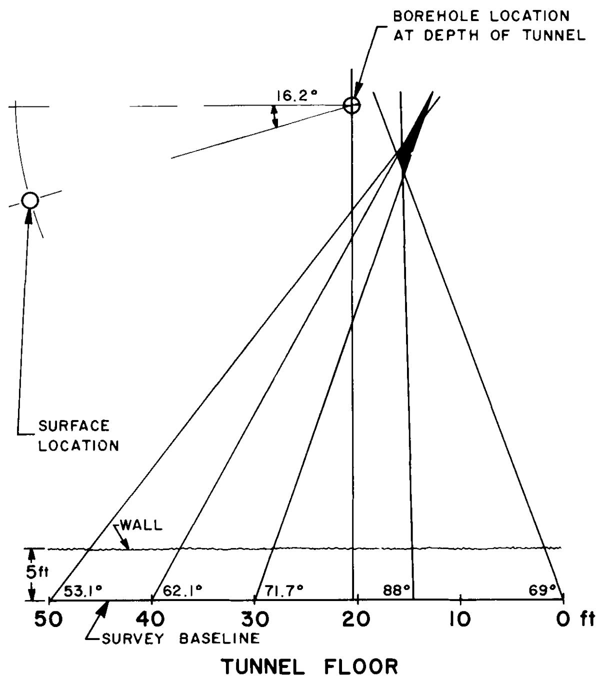

FIGURE 7. - Results of field test at Ft. Ritchie, Md.

The Corps of Engineers proceeded to drill a series of 2-in pilot holes on 8-in centers starting at the suggested location, and on the 11th hole, water was struck at the location shown. The location error of approximately 4.5 ft could have been caused by several factors including metal structures in the tunnel, a large diesel-electric generator 100 ft away, or tilt of the coil in the hole. The effect of core-tilt can be quite significant (see appendix B for analysis), but it can be minimized by using a small-diameter transmitter to insure that it hangs vertically and by taking two sets of readings--one with the transmitter above the tunnel and the other with the transmitter an equal distance below the tunnel. The area enclosed by the triangulation plot will include the borehole.

The effects of conducting bodies are generally impossible to predict, but they are not a problem unless they lie very close to the transmitter or receiver.

CONCLUSIONS

A technique has been described for locating boreholes in underground tunnels using equipment developed under the Bureau's trapped miner program. Theoretical calculations and field measurements have demonstrated that accuracies of the order of 1° are possible in the field.

The Bureau is presently working on an advanced technique using frequencies below 20 Hz in conjunction with a magnetometer. Preliminary results indicate the system will find cased holes at distances in excess of 100 ft. A complete description will be available when the contract is completed, possibly by late 1978.

APPENDIX A.--TRANSMITTER COIL DESIGN

The object of the transmitter coil design is to maximize the coil magnetic moment M = INA for a given package size, weight, and available transmitter power. For convenience, the following terms are defined:

I = Coil current, RMS.

N = Coil turns.

A = Coil area, square meters.

D = Coil diameter, meters.

R_w = Wire resistance, ohms per meter.

α = Wire density, kilograms per cubic meters.

R_o = Transmitter internal resistance.

V_o = Transmitter open circuit voltage, root mean square.

R_c = Total coil resistance, ohms.

M = INA, ampere-square meter.

P_w = Wire resistivity, ohm-meters.

W = Coil weight, kilograms.

d = Wire diameter, meters.

If the coil is tuned to the transmitter frequency so that the coil current is limited only by its direct current (dc) resistance, the following results will be achieved:

$$I = \frac{V_o}{R_o + R_c}, \qquad \text{(A-1)}$$

$$R_c = \pi D N R_w, \qquad \text{(A-2)}$$

$$W = \pi D N \frac{\pi d^2 \alpha}{4}, \qquad \text{(A-3)}$$

and

$$R_w = \frac{4P_w}{\pi d^2}. \qquad \text{(A-4)}$$

If the wire diameter from A-3 and A-4 is eliminated, a relationship between N and W will result

$$N = \frac{W R_w}{\pi D \alpha P_w}. \qquad \text{(A-5)}$$

Using this expression for N in the equation for M the following is obtained:

$$M = \frac{\dfrac{V_o DWR_w}{\alpha \ P_w}}{4\left[R_o + \dfrac{WR_w}{\alpha P_w}\right]^2} . \tag{A-6}$$

By differentiating A-6 with respect to R_w and setting equal to zero, the optimum wire resistance for a given coil weight and diameter is found. This procedure gives

$$R_w = \left[\frac{\alpha \ P_w R_o}{W}\right]^{1/2} . \tag{A-7}$$

Using equations A-2 and A-5, these expressions can be rewritten as

$$R_c = R_o . \tag{A-8}$$

That is, for a given weight, the best coil is one that matches the transmitter for optimum power transfer. The magnetic moment is given by

$$M = \frac{V_o D}{8R_w} . \tag{A-9}$$

For the present transmitter and package No. 18 enameled wire was used which gives

R_o = 0.77 ohm,

V_o = 1.6 v,

for No. 18 copper wire,

P_w = 1.72×10^{-8} ohm-m,

α = 8,920 kg/m^3,

R_w = 0.02095 ohms/m,

and D = 0.064 m.

Then W = 0.27 kg (0.6 lb),

M = 0.61 A-m^2,

and N = 184 turns.

APPENDIX B.--COIL TILT ERRORS

The transmitter coil may not hang vertically in the borehole. Either the cylinder may be cocked in the hole or it may be resting against the side of the hole which is not vertical.

The purpose of this exercise is to calculate the probable effect of coil tilt on location accuracy as well as to minimize it. Consider a spherical coordinate system with the transmitter at the origin as shown in figure B-1.

The coil is tilted in the direction $\hat{R}$ and has a magnetic moment $\hat{M}$.

Assume the tunnel runs paralled to the $\hat{X}$ axis. The receiver coil is located at the coordinates x, y, z in the tunnel.

The problem is to find the direction of minimum magnetic field in the XY plane and determine the direction in which the coil will point. Figure B-2 shows a plane view of the coil in the null direction.

At null, the plane of the coil is alined with the component of the H field in the XY plane, or

$$\tan \Psi = \frac{H_y}{H_x} . \tag{B-1}$$

Therefore, to find the null direction the X and Y components of the magnetic field are found.

In the following analysis, it is assumed that rock conductivities are low enough to use the static fields of a magnetic dipole.

The tilted dipole can be represented as three dipoles alined with the X, Y, and Z axes as follows:

$$M_z = M \cos \theta_o , \tag{B-2}$$

$$M_x = M \sin \theta_o \cos \phi_o , \tag{B-3}$$

and

$$M_y = M \sin \theta_o \sin \phi_o , \tag{B-4}$$

where

$$M^2 = M^2_x + M^2_y + M^2_z . \tag{B-5}$$

The static fields due to each dipole component can be written as follows: At the receiver coil (x,y,z) it is found that

$$H_{m\,x} = \frac{M_x}{4\pi r^5} \left\{ 3\ x z \hat{z} + 3\ x y \hat{y} - (y^2 + z^2 - 2x^2)\ \hat{x} \right\} , \tag{B-6}$$

$$H_{m\,y} = \frac{M_y}{4\pi r^5} \left\{ 3\ xy\ \hat{x} + 3\ yz\ \hat{z} - (x^2 + z^2 - 2y^2)\ \hat{y} \right\} , \tag{B-7}$$

and

$$H_{m\,z} = \frac{M_z}{4\pi r^5} \left\{ 3\ xz\ \hat{x} + 3\ yz\ \hat{y} - (x^2 + y^2 - 2z^2)\ \hat{z} \right\} , \tag{B-8}$$

where $r^2 = x^2 + y^2 + z^2$.

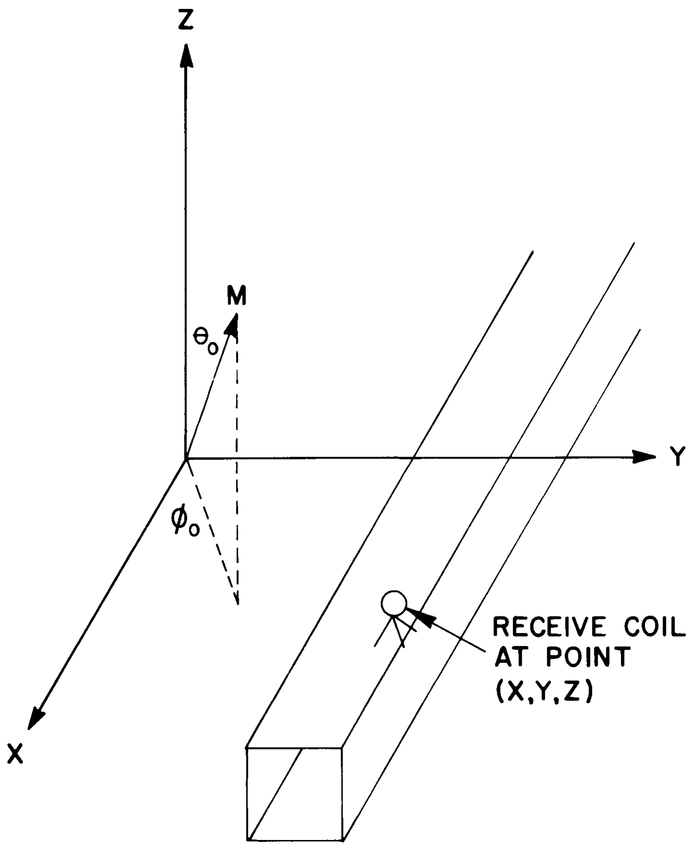

FIGURE B-1. - Coordinate system with the transmitter at the origin.

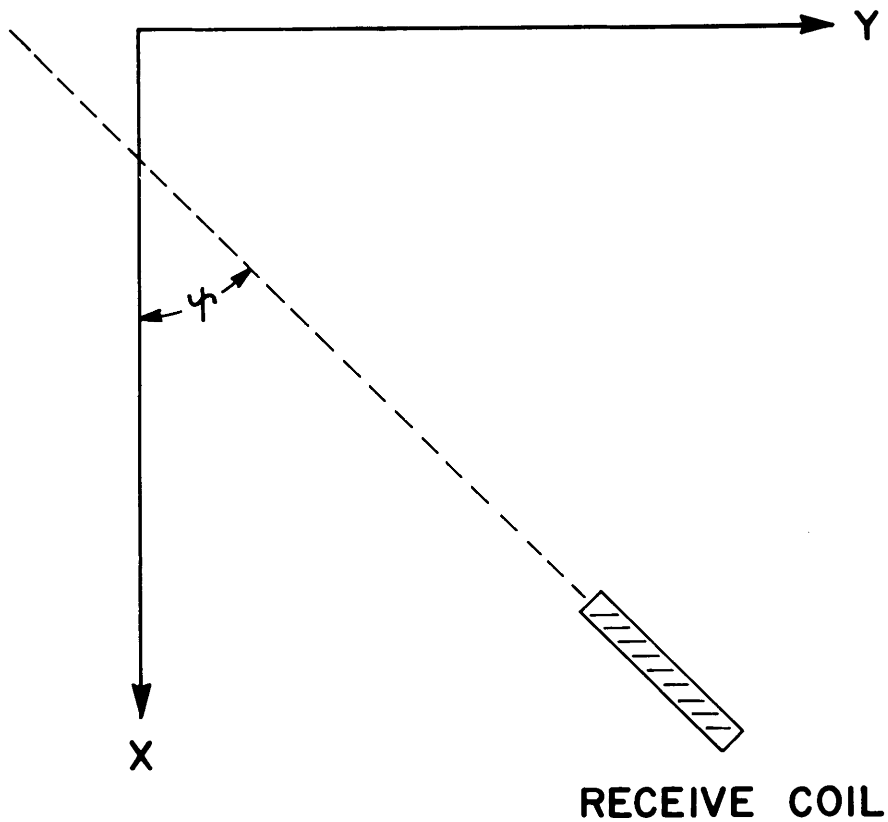

FIGURE B-2. - Plane view of the coil in the null direction.

Each of these fields has x and y components.

By combining the x and y components, H_x and H_y are found as

$$H_x = \frac{1}{4\pi r^5}\left\{3\ M_z xz + 3\ M_y xy - M_x\ (z^2 + y^2 - 2x^2)\right\}, \tag{B-9}$$

and

$$H_y = \frac{1}{4\pi r^5}\left\{3\ M_z yz + 3\ M_x xy - M_y\ (x^2 + z^2 - 2y^2)\right\}. \tag{B-10}$$

Then from equation B-1,

$$\tan\Psi = \frac{H_y}{H_x} = \frac{3\ M_z yz + 3M_x\ xy - M_y\ (x^2 + z^2 - 2y^2)}{3\ M_z xz + 3M_y\ xy - M_x\ (y^2 + z^2 - 2x^2)}. \tag{B-11}$$

It can be seen that if $\theta_o = 0$ then M_x and $M_y = 0$ (no tilt), and $\tan\Psi = \frac{y}{x} = \tan\phi$ as expected, where ϕ is the true angle.

If $\Psi = \phi + \delta\phi$ is allowed in equation B-11 where $\delta\phi$ is error in angle caused by coil tilt and convert to cylindrical coordinates by letting

$$x = \rho\cos\phi,$$

$$y = \rho\sin\phi,$$

$$\rho^2 = x^2 + y^2.$$

Then it can be shown that

$$\tan\delta\phi = \frac{(\rho^2 + z^2)\tan\theta_o\ \sin(\phi - \phi_o)}{3\rho z + (2\rho^2 - z^2)\tan\theta_o\ \cos(\phi - \phi_o)}. \tag{B-12}$$

Figure B-3 shows the effect of coil tilt on location accuracy. The values of the tilt parameters were taken from the Ft. Ritchie, Md., experiment. Since the transmitter package diameter was nearly equal to the well diameter, we assumed the transmitter coil was alined with the wellhole; in addition, the wellhole is assumed to be straight. This gives $\theta_o = 3.08°$ and $\phi = +16.2°$. Figure B-3 shows reasonable agreement between the theoretical calculations and the measured data.

Minimizing the Error

Usually $\tan\theta_o \ll 1$, then the minimum value of the $\tan\delta\phi$ occurs when $z = \rho$. Since ρ is not known, this condition can be met only by using reasonable judgment when the transmitter is positioned in the hole.

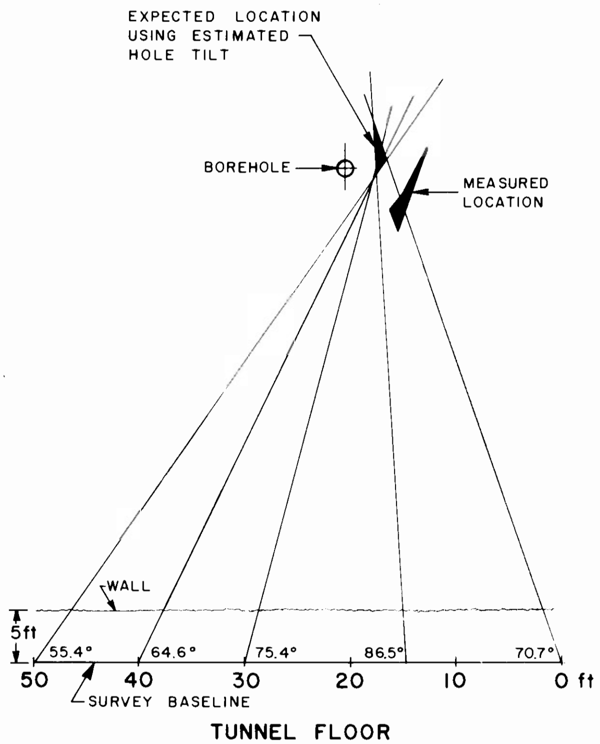

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FIGURE B-3. - Effect of coil tilt on location accuracy.

When $\theta_o < \pm 6°$ and $1/2 < z/\rho < 4$ then equation B-12 can be written

$$\tan \delta \phi = \frac{\rho^2 + z^2}{3\rho z} \tan \theta_o \sin (\phi - \phi_o). \tag{B-13}$$

Equation B-13 is odd in z. If the angle Ψ_1 is measured when the transmitter is z_1 ft above the tunnel and an angle Ψ_2 is measured at the same horizontal location when the transmitter is z_1 ft below the tunnel, then the true angle ϕ is found from the average of Ψ_1 and Ψ_2 as follows:

$$\phi = \frac{\Psi_1 + \Psi_2}{2} \tag{B-14}$$

This is shown in table B-1 using the estimated hole tilt values of the field test.

TABLE B-1. - Minimizing error by measuring above and below tunnel

(θ_o = 3.08°, ϕ_o = 16.2°, x = 29.5 ft, y = 48 ft, ϕ = 58.4°)

Z_1, ft	Measured angle, degrees	Error, degrees	Average	Net error, degrees
+5	64.4	6.0	55.9	-2.5
-5	47.4	-11.0		
+50	59.8	1.4	58.4	.0
-50	57.0	-1.4		

In this case, the ideal value for z is approximately 50 ft, but it can be seen that over the range of 10 to 1, the error can be significantly reduced.

In any case, the measured angles bracket the true value so that the actual location will always be within the outlined quadrangle as long as

$$|z| > \rho \tan \theta_o ,$$

and $$|z| < \rho / \tan \theta_o .$$

An example of this is shown in figure B-4. The solid lines are the calculated null directions with the transmitter above and below the receiver. The dashed lines are derived from the arithmetic average of the two angular readings of each horizontal location and are virtually dead center.

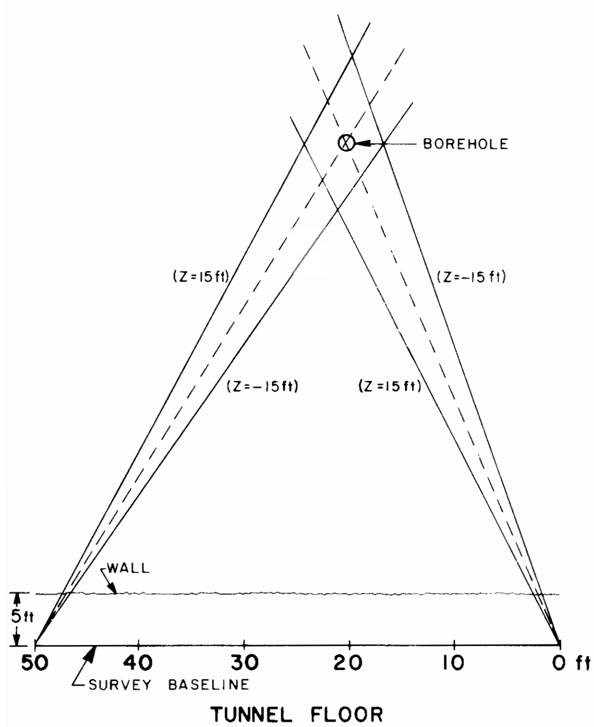

FIGURE B-4. - Effect of moving transmitter above and below tunnel center line on location accuracy.