BOREHOLE LOCATION SYSTEM CONCEPT DEMONSTRATION TESTS

Prepared for

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by

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16. Abstract

This report describes the feasibility test of an electromagnetic method for locating boreholes, with or without casing, that have been drilled in conjunction with mining operations but whose location with respect to the tunnel is not precisely known. The first tests were conducted with the cooperation of the Kerr-McGee Corporation, Church Rock Mining Operations, New Mexico, in September 1977. These tests demonstrated that accuracies of better than ±5% of range and ±1° of bearing can be achieved with a simple system and setups. Subsequent tests, in January 1978, on a horizontally drilled pipe line river crossing application, by Titan Contractors of Sacramento, California, demonstrated that accuracies of better than one-half percent of range and a few tenths of one degree of bearing can be achieved by using refined techniques. The demonstration tests were done at ranges on the order of 100 to 200 feet but the method is capable of working at much greater distances.

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FOREWORD

This report was prepared by Develco, Inc., Sunnyvale, California, under USBM Contract Number J0177074. The contract was initiated under the Industrial Hazards and Communications Program. It was administered under the technical direction of Pittsburg Mining and Safety Research Center with H. Kenneth Sacks acting as Technical Project Officer. H.R. Eveland was the contract administrator for the Bureau of Mines. This report is a summary of the work recently completed as a part of this contract during the period of May 1977 to January 1978. This report was submitted by the authors on May 5, 1978.

There were no inventions or patents disclosed as a result of work performed on this contract.

We would like to thank Dr. H.K. Sacks of the USBM Pittsburg Mining and Safety Research Center, and Rodger F. Sturgeon and his associates of the Kerr-McGee Corporation, Church Rock Operations, for their support and assistance. We are also grateful to Sandia Corporation and the Department of Energy for allowing use of the ELF receiver supplied by Develco for a previous project. We would also like to thank Martin Cherrington and others of the Titan Contractors Corporation for their support.

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1. INTRODUCTION

This report describes the feasibility test of an electromagnetic method for locating boreholes, with or without casing, that have been drilled in conjunction with underground mining operations but whose location with respect to the tunnel is not precisely known. The Bureau of Mines has conducted successful experiments[1] with uncased holes where a transmitting magnetic dipole antenna, operating at a frequency of about 1000 hertz in the borehole, was located by triangulation methods from within the tunnel. However, the relatively high frequencies used do not permit direct application to cased holes and triangulation is not practical in some situations. The method used in the demonstration tests overcomes these limitations by using very low frequencies to penetrate the casing, and a vector field detector which obtains hole location information from a single position in the tunnel. The detector can be located more than 100 feet from cased boreholes, or even further for uncased holes. In addition, the method has potential value in other mine surveying problems which are discussed in this report.

The tests were conducted with the cooperation of the Kerr-McGee Corporation, Church Rock Mining Operations near Gallup, New Mexico on September 9 through 12, 1977. They have had hole location problems, and inquired at the Bureau of Mines for a solution which provided a real case to demonstrate the method proposed by Develco in 1976. The test objectives were first to demonstrate the technique by making measurements on a known ventilation shaft, and then to verify the relative position of a new ventilation shaft with respect to a new haulage drift being tunnelled towards it. Existing components, and some new prototype equipment, was assembled without consideration of field operation design in order to achieve an inexpensive demonstration, These objectives were successfully accomplished as discussed in the following sections. Subsequent to the Kerr-McGee operation, an application involving the horizontal drilling of pipe line river crossings was encountered which offered an opportunity to test the method as a means of drilling navigation which may also be of use in mine operations. The successful results of this cooperative effort are described in Appendix IV and were of considerable benefit in refining techniques.

2. THEORY OF OPERATION

The borehole location system incorporates a borehole transmitter, generating an ac magnetic dipole moment at low frequencies (a few hertz to 10's of hertz typically) to penetrate steel casings with minimum attenuation, and a 3-axis receiver. The receiver is set up in a mine drift close to (100 to 200 feet typically) the expected hole location, and the transmitter is lowered in the borehole to about 100 to 200 feet above the drift, i.e., about the same order as the distance from hole to receiver. In the case of operation without communication between the drift and the surface, the transmitter is then lowered in known steps of 5 to 20 feet, at intervals of a few minutes, to permit data logging at each stop. The number of data points will depend on the data reduction technique used and the data quality. For the simple graphical methods used in the demonstration a large number of points are preferable, but an estimate can be calculated from 2 points at appropriate locations.

2.1 LOCATOR EQUATIONS

For the geometry illustrated in Figure 1, the radial and tangential magnetic field components at the receiver, which result from a vertical magnetic dipole with a moment m operating through a steel casing with an attenuation A, are as follows:

$$H_r = \frac{2Am}{4\pi r^3} \cos \theta$$

$$H_\theta = \frac{Am}{4\pi r^3} \sin \theta .$$

These expressions assume that the attenuation due to the earth's conductivity is negligible for the short ranges and low frequencies involved in this case.

Since the receiver is a leveled 3-axis vector magnetometer, the vertical and horizontal components actually measured are related to these expressions by

$$H_v = H_r \cos \theta - H_\theta \sin \theta = \frac{mA}{4\pi r^3} [2 \cos^2\theta - \sin^2\theta]$$

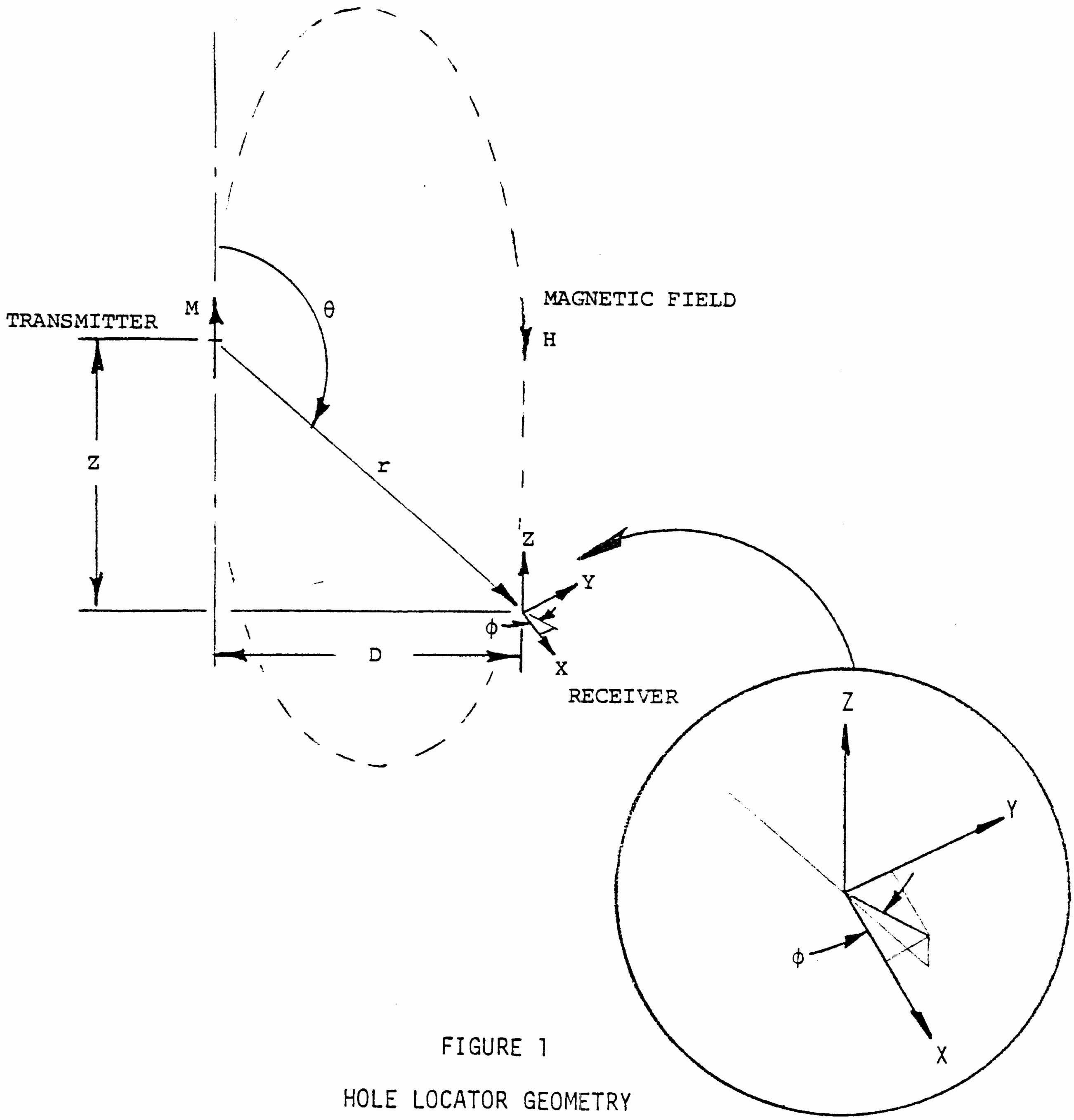


FIGURE 1

HOLE LOCATOR GEOMETRY

and

$$H_h = H_r \sin\theta + H_\theta \cos\theta = \frac{mA}{4\pi r^3}[3 \sin\theta \cos\theta].$$

Using the expressions

$$r = (Z^2 + D^2)^{1/2}$$

$$\sin\theta = D/r$$

$$\cos\theta = Z/r$$

the field's rectangular components can be expressed in terms of the vertical and horizontal distance from the transmitter to receiver, Z and D, respectively, as

$$H_v = \frac{AM}{4\pi}(2Z^2 - D^2)(Z^2 + D^2)^{-5/2} = H_z$$

$$H_h = \frac{AM}{4\pi} 3ZD(Z^2 + D^2)^{-5/2} = H_x \cos\phi + H_y \sin\phi$$

where ϕ is angle of the horizontal field with respect to the receiver coordinates.

These latter expressions have characteristic patterns which are plotted in Figures 2 and 3, normalized to the maximum vertical field at Z=0 which is defined as the transmitter antenna (center) elevation equal to the receiver elevation.

The direction, or bearing azimuth (A_z), of the borehole from the receiver is given directly by the direction of the horizontal field

$$\phi = \arctan \frac{H_y}{H_x}.$$

This is best evaluated at the horizontal field maximum which occurs when the transmitter is located at Z = ±D/2. Quadrant resolution must be determined from the relative phases of components. The simplest way to do this is by observation of the relative polarity of the three components with respect to the antenna's flux line direction. It can be seen that when the receiver is below the transmitter, the direction from the receiver to the transmitter is opposite to the phase of the horizontal

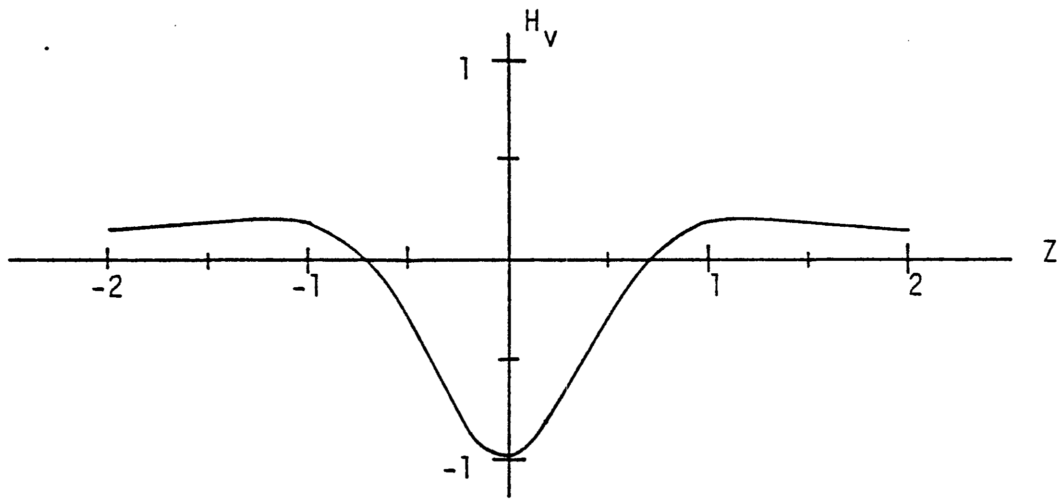


FIGURE 2

VERTICAL FIELD PATTERN AT RECEIVER

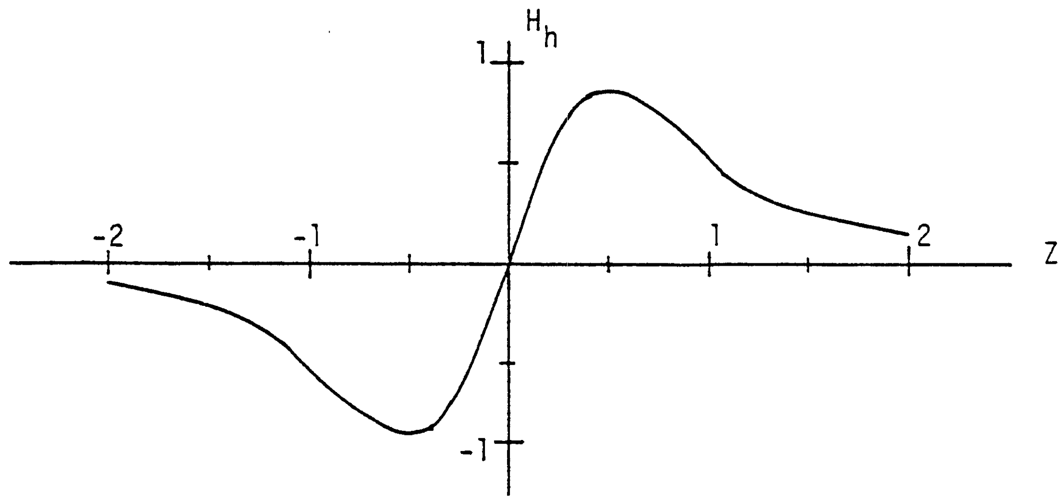


FIGURE 3

HORIZONTAL FIELD PATTERN AT RECEIVER

components with respect to the vertical component (e.g., if the measured values of X, Y and Z are in phase and defined as +, the direction to the transmitter is -X, -Y). The reverse is true when the receiver is above the transmitter.

The distance D, or range, of the borehole from the receiver can be determined in several ways. The most accurate way would be to correlate all data points with the above equations using a computer; but this was beyond the scope of this program. However, under the relatively good signal-to-noise conditions expected, suitable accuracy can be achieved in this application by simpler graphical or computational methods. For example, the value could be obtained from the derivative of the horizontal field at its peak, as inferred above, but the peak is too broad to permit any more than a rough estimate in practice.

In those cases where the borehole extends sufficiently below the receiver elevation, the distance D can be determined from the distance traveled by the transmitter between zeroes of the vertical field, at Z_A and Z_B, using the relationship

$$D = [\pm\sqrt{2}\ Z]_{H_{v=0}}$$

or

$$D = \left[\pm\frac{Z_A - Z_B}{\sqrt{2}}\right] .$$

If the lower vertical field zero cannot be obtained the horizontal field zero crossing, Z_0, which occurs at zero elevation, can be used instead, so

$$D = \pm[\sqrt{2}(Z_A - Z_0)].$$

An alternate procedure is to calculate D by determining the rate of change of the horizontal field, at Z=0, with respect to the known change of Z. At H_h = Z=0

$$\frac{dH_h}{dZ} = \frac{3Am}{4\pi} D^{-4}$$

and

$$H_v = -\frac{Am}{4\pi} D^{-3}$$

therefore

$$D = -3 \left[H_v \frac{dZ}{dH_h} \right]_{H_h=0} .$$

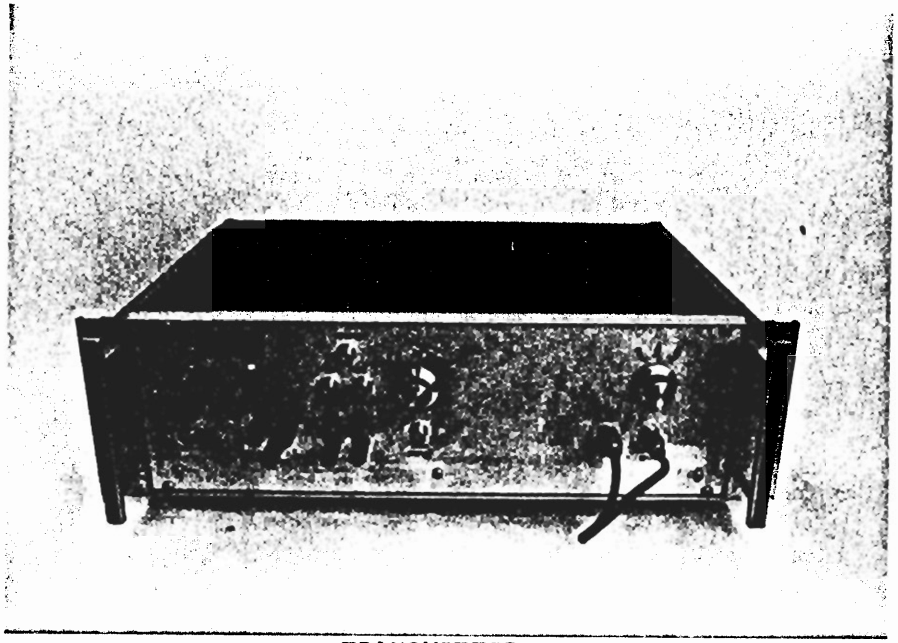
There are, of course, many cases where the borehole does not reach down to the same elevation as the receiver. In these instances it is either necessary to extrapolate, if the resulting accuracy is adequate, or to use a more involved calculation procedure.

These equations are strictly applicable only when the borehole axis, or the path that the transmitter follows, is perfectly parallel to the receiver vertical axis. Although a detailed error analysis is beyond the scope of this report, an idea of the effects of a tilted axis and other causes can be obtained from the results discussed in Section 4.6. Again, it would be possible to resolve all such factors with a more complex measurement and/or data reduction calculation.

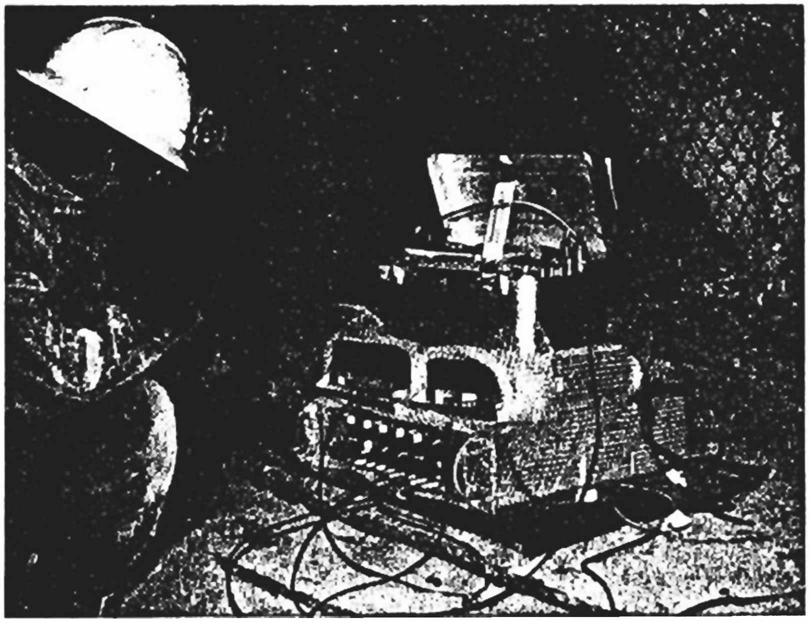
3. EQUIPMENT DESCRIPTION

The equipment illustrated in Figure 4 was used in order to demonstrate the borehole locator concept feasibility as simply as possible. The solenoid type magnetic transmitting antenna was directly driven, through 2000 feet of 2-conductor, 12-gauge cable supplied by Kerr-McGee, to avoid the complexity of building a low power resonant antenna for downhole use. A simple push-pull type transmitter was built to drive the antenna since standard amplifiers are not readily available to operate at the high current levels and low frequencies required. A standard Develco Model 105395 Fluxgate Magnetometer was used to provide a compact, precisely orthogonal 3-axis receiver sensor. The ELF receiver, which was previously supplied by Develco to Sandia Laboratories for other prototype test work, was modified and used to provide coherent signal detection. Since signal phase is important, a stable crystal oscillator was built for both the receiver and transmitter. In addition, a spare preamplifier was adapted to compensate for the signal reduction resulting from the casing attenuation.

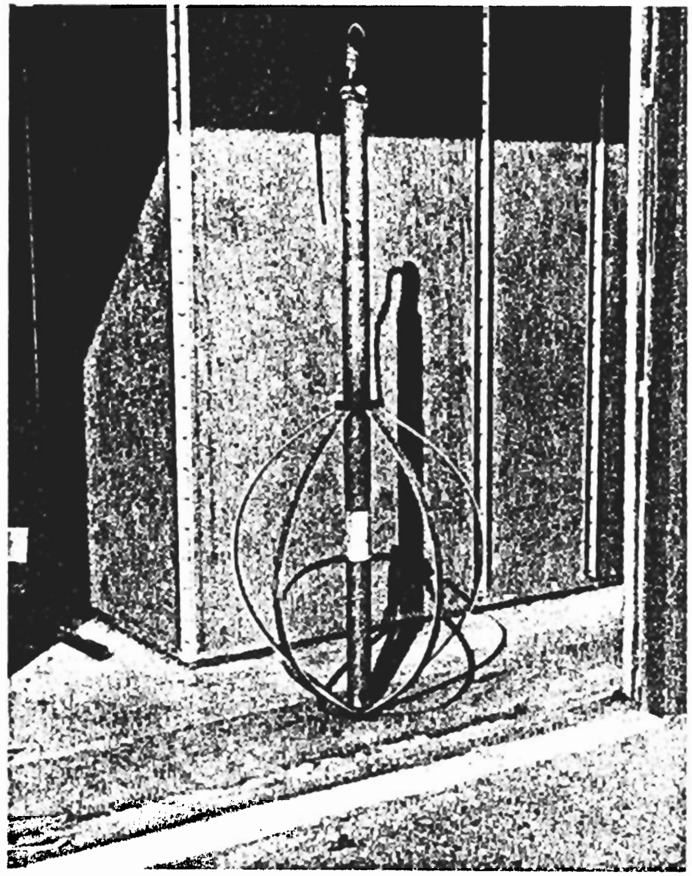
The ventilation shaft casings at the Kerr-McGee Mine are typically 5 feet in diameter and 5/8 inch thick at the elevations of interest. (There is one shaft, Vent #3, with 7/8 inch thick casing at the bottom but no measurements were made in it due to a last minute change. The casing data for the two test shafts are based on available data for Vent #5, and Vent #1 is believed to be the same.) The steels used are based on ASTM specifications A441 and, sometimes, A36. Both are roughly .2% carbon steels, and although there is no specific electrical data on these alloys, the information published by Bozorth[2] for carbon steel seems to be typical. That is, the relative initial permeability, μ_0, is on the order of 100 (quenched) to 200 (annealed) and the conductivity is on the order of 5 to 8 x 10^6 Siemens/meter. An estimate of the casing attenuation was made based on the formulas in a paper by Shenfeld.[3] The calculations suggested that attenuation could be on the order of 3 to 6 dB at 2 Hz, 8 to 12 dB at 4 Hz, and 16 to 22 dB at 8 Hz. The field measurements suggested the actual attenuations were on this order although precise confirmation could not be obtained.



TRANSMITTER



RECEIVER



ANTENNA

Figure 4A. BOREHOLE LOCATION DEMONSTRATION EQUIPMENT

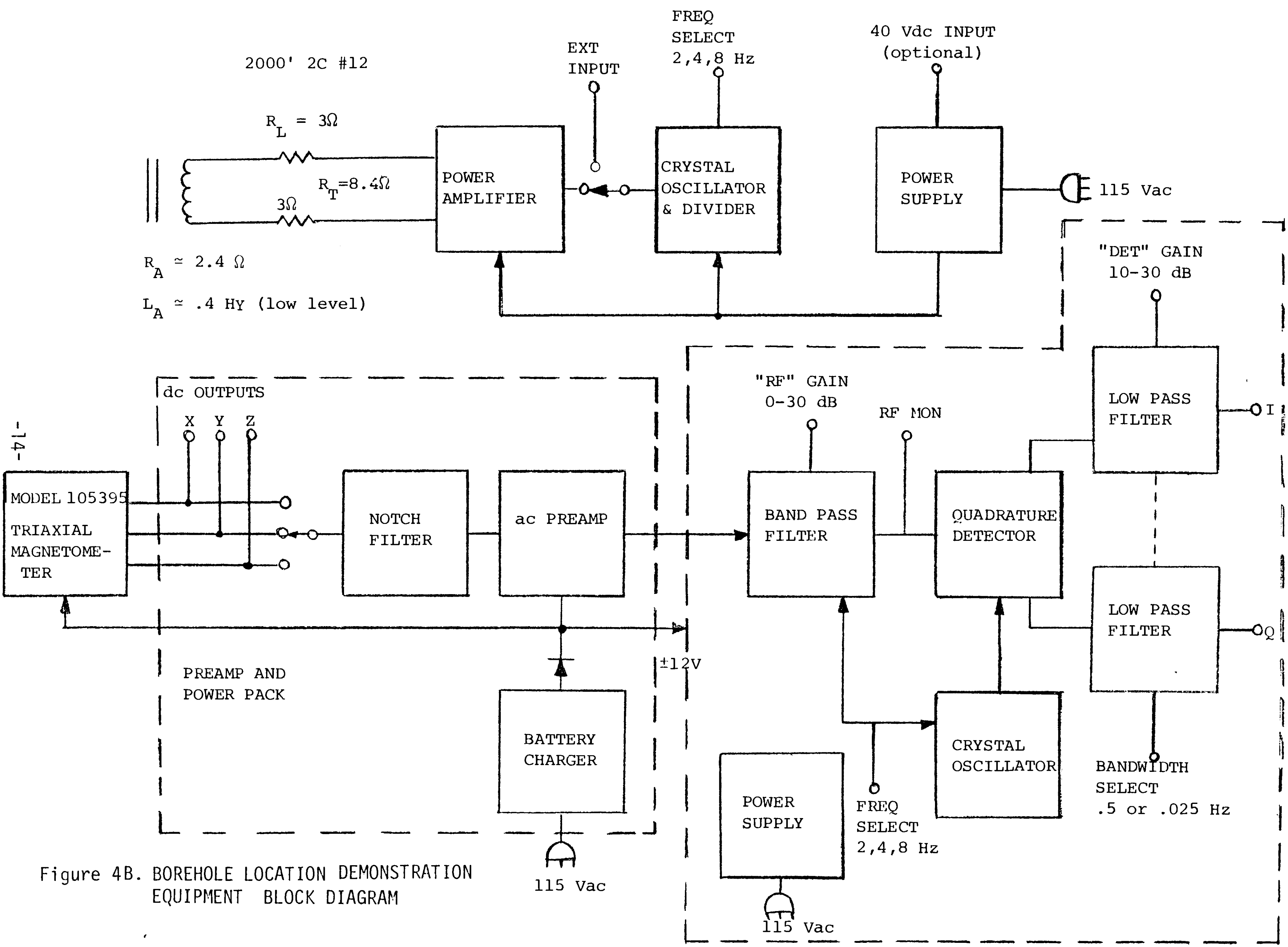


Figure 4B. BOREHOLE LOCATION DEMONSTRATION EQUIPMENT BLOCK DIAGRAM

An iron cored solenoid was used as the transmitting antenna, or magnetic dipole source, in order to provide adequate signal levels through the shaft casing with a structure of convenient size. The core of the antenna consists of a stack of soft electrical steel alloy, laminated to minimize eddy current loss, approximately 0.8 inch x 2 inch x 5 feet (0.02 x 0.05 x 1.5 meters) in size and weighing about 28 pounds (12.7 kg). The core was wound over nearly the full length with about 1100 turns of 16-gauge magnet wire to achieve core saturation, and maximum magnetic moment, with a roughly square wave current on the order of 3 amperes peak. The moment of the fundamental component at 2 Hz was approximately 1750 $A \cdot m^2$ peak or 1240 $A \cdot m^2$ rms, based on the field measured at a known radius, which agrees with the value predicted. (The effective moment at higher frequencies was slightly less because of waveform and response variations.) The core assembly was potted in a fiberglass tube for hydrostatic protection resulting in a final assembly approximately 3 inches in diameter by 7 feet long and weighing about 50 pounds. Centralizers were used in case it was necessary to keep the antenna away from the casing walls. Their size was significantly less than the casing diameter but it is believed the antenna was nearly in the center of the hole when it was hanging free.

The equatorial field ($H\theta = Hz$ at $Z=0$) signal strengths produced by a moment of 1240 $A \cdot m^2$ rms at 2 Hz operating through casing, with the calculated attenuations above, are plotted in Figure 5 as a function of radial range. The maximum magnetometer noise is on the order of 5 μG, or 0.4 mA/m, peak to peak in the bandwidth from 1 to 10 Hz. The rms noise in a unit bandwidth, BW, can be calculated from[5]

$$\text{Noise (rms)} = \frac{\text{Noise p-p}}{5\sqrt{BW}} = \frac{0.4 \text{ mA/m}}{5\sqrt{9 \text{ Hz}}} = 26\ \mu\text{A/m}/\sqrt{\text{Hz}}.$$

Thus the equivalent magnetometer noise levels in the minimum receiver post-detection bandwidth of .025 Hz, as discussed below, is 4.2 μA/m rms. It can be seen from Figure 5 that in order to achieve a signal-to-noise ratio of on the order of 30 to 40 dB, which is necessary for satisfactory use of the simple graphical methods described in Section 2.1, at ranges over 100 feet that operation at 2 Hz is necessary.

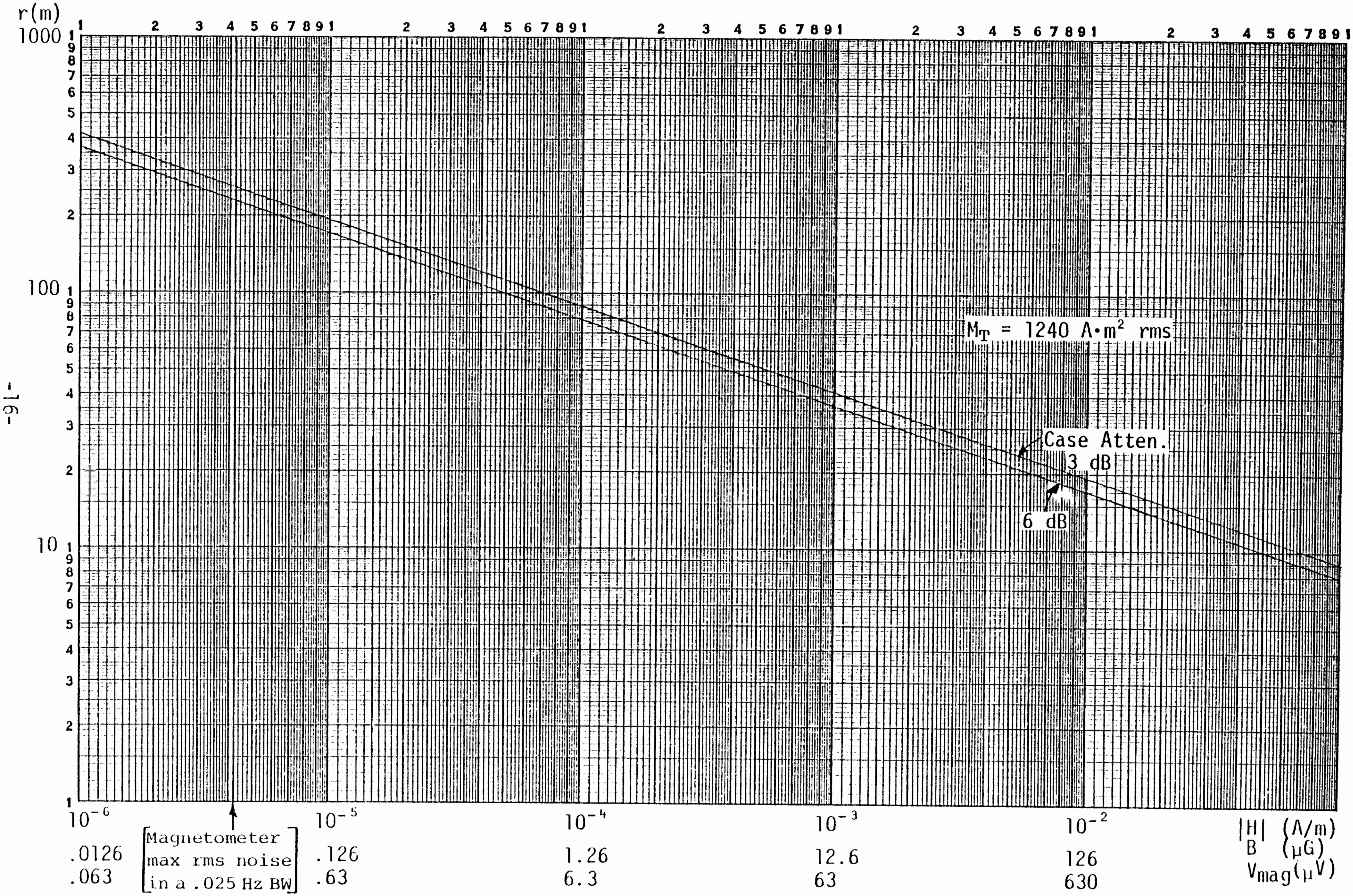


Figure 5. Plot of Field Strength at 2 Hz

It is important to note that although the magnetometer noise level is relatively high, for general receiving purposes, this may not be a disadvantage in many applications. For example, Bensama's[4] data on coal mine noise at less than 60 Hz suggests that typical mine noise is on the same order as the magnetometer noise in many cases and even worse in some (e.g., as high as 1 mA/m in a 3-4 Hz bandwidth). Thus a better detector would not be of any help if this data can be considered representative of the majority of mines. Of course, in those cases where longer ranges, etc., are very important and environmental noise is not a factor, a field coil arrangement could achieve much better performance without too much trouble.

The output of each magnetometer axis is manually switched to the "Sandia" ELF receiver for amplification, detection and filtering.

From Figure 5 it can be seen that gains from 70 to 130 dB are needed to give output signals on the order of several volts over the range of signal levels of interest. Since the ELF receiver has a maximum gain of 60 dB (30 dB each in pre- and post-detection amplification) it was necessary to add 70 dB of preamplification. This was achieved by mounting a preamplifier assembly in the battery box, as close to the magnetometer as possible to minimize noise pickup, and adding an ac coupled 60 Hz input notch filter, to prevent dc or ac saturation. However, the dc outputs were brought to separate connectors so the magnetometer could be used as a compass for alignment purposes, if necessary.

Two 12-volt (nominal), 4.5 ampere-hour Gel Cel batteries were used to supply the magnetometer and receiver and provided an operating life in excess of 90 hours at current drains of less than 50 mA. A charging circuit was built into the battery/preamplifier case and which was used along with the receiver power supply when ac power was available.

The primary reason for using the "Sandia" ELF receiver, in addition to availability, is that it provides the coherent detection to determine the signals' absolute amplitude and phase required in this application. In this case, since the signal and local oscillator phase relationship is arbitrary but constant, the detection is done with the normal and quadrature components of the local oscillator. The amplitude and relative phase of the signal can be calculated from the quadrature-detected dc components

$$I = V \cos \theta \text{ and } Q = V \sin \theta$$

where V is the amplitude, and θ is the relative electrical phase angle in this case.

The most direct method of insuring that the transmitter and receiver phases remain constant is to use the oscillator in one, and wire a reference signal to the other. Although this was not feasible in the Kerr-McGee mine case, provisions were made to do so since it will be useful in some cases (e.g., Titan, Appendix IV). Since the original RC oscillator in the ELF receiver had too much drift for this application, a crystal controlled oscillator and divider was constructed to replace it. At the same time, receiver operation was changed from selectable values of 5, 10 and 20 Hz to 2, 4 and 8 Hz to insure adequate signal strength with casing attenuation predicted above. An identical oscillator was also constructed for use in the transmitter. Although there was some observable drift when the transmitter and receiver were at significantly different temperatures, itwas low enough to obtain a consistent set of data.

The receiver also provided the required filtering. A predetection filter with a bandwidth of about 0.27 times the center frequency suppressed the signal harmonics. A selectable post-detection low pass filter determined the receiver noise bandwidth; the 0.5 Hz position was used under high signal conditions and provided relatively quick settling; the 0.025 Hz bandwidth provided the required noise suppression under relatively low signal conditions. In addition, simple averaging was used under some conditions when more accurate results were desirable.

Table 1 provides a summary of the demonstration equipment's general characteristics.

TABLE 1

BOREHOLE LOCATION DEMONSTRATION EQUIPMENT
GENERAL CHARACTERISTICS

TRANSMITTER	
Operating Frequency:	2, 4, 8 Hz
Drive Current (square wave):	±3 A peak
Magnetic Dipole Moment (Fundamental Component)	1240 $A \cdot m^2$ rms
RECEIVER	
Operating Frequency:	2, 4, 8 Hz
Post Detection Bandwidth:	.5, .025 Hz
System Gain (approx.):	70 to 130 dB
System Noise Level (equivalent in .025 Hz BW):	<4.2 μA/m rms
3-AXIS MAGNETOMETER (MODEL 105395)	
Range:	±1 gauss* each axis
Scale Factor:	5 V/G
Accuracy:	<±1% of full scale, 0-60°C
Linearity:	<±0.1% of full scale
Axis Alignment:	<±0.2° relative to case referenced coordinates
Frequency Response:	dc - 1 kHz
Broadband Noise:	<5 μG p-p 0.1 - 1 Hz
	<5 μG p-p 1-10 Hz
	<50 μG p-p 10-500 Hz

*1 gauss equivalent to $\frac{10^3}{4\pi}$ A/m in free space.

4. RESULTS

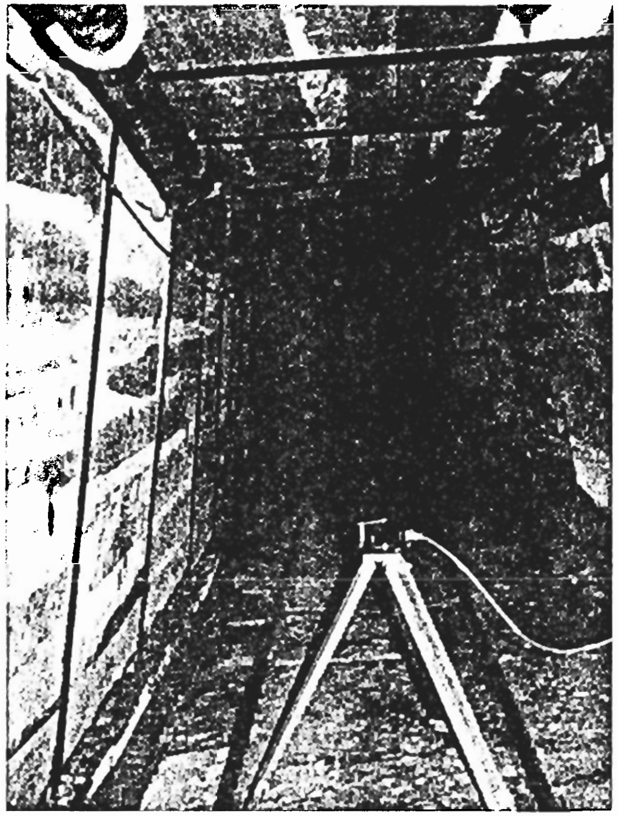
4.1 SETUP

Three cased hole location measurements were made at the Kerr-McGee Uranium Mine, Church Rock Operations in Gallup, New Mexico on September 10 and 11, 1978. These consisted of a first measurement on the 1-4 level of the mine, at a depth of about 1500 feet and about 50 feet from the operational ventilation shaft #1; a second on the 1-5 level (about 130 feet below 1-4 and level with the vent bottom), about 80 feet from Vent #1; and a third in the 1-4 level about 130 feet from the new shaft for Vent #5 which had not yet been reached by the tunneling. The first two measurements served as a check on system operation, since the location of Vent #1 is fairly well known, and the last provided Kerr-McGee with a position check on the "unknown" location of Vent #5. The 5-foot diameter vents were lined with 0.625-inch thick steel casing (Specification A441) at the depths of interest.

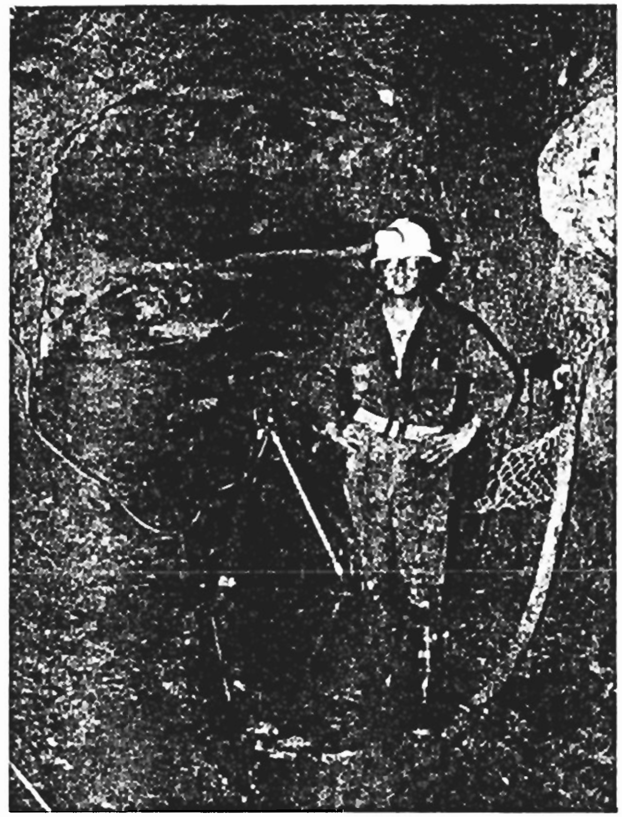
It was necessary to conduct these tests on a weekend so that Vent #1 could be shut down, which is not permitted during a normal working shift. On Saturday, repair work was being conducted on the only hoist shaft, which was operated intermittently, so movements had to be carefully timed. This did not leave time to accurately measure the receiver locations for Vent #1 so they had to be rechecked, as well as possible, later. There was not much time for actual measurements at Vent #5 on Sunday either due to the long distance from the elevator shaft (2 miles), lack of communications in the new tunnel, and the surface setup time over the new shaft. However, in spite of the difficulties and because of fine support from the Kerr-McGee maintenance crew, a very successful set of measurements was obtained.

The receiving magnetometer was set up in an arbitrary location at each test station, as shown in Figure 6. No special effort was made to avoid conditions that might affect the results, such as the steel pipes, beams, rail tracks and power lines that can be seen in the photographs. Although the mine surveys are typically referenced to the left track, the setups were made roughly midway between the tracks for improved stability with

VENT #1 LEVEL 1-4
A



VENT #1 LEVEL 1-5
B



VENT #5 LEVEL 1-4
C

FIGURE 6

RECEIVING (MAGNETOMETER) STATION SETUPS

the simple tripod used. The magnetometer +Y axis was oriented towards local magnetic North in each case and leveled with a bubble level. (The magnetometer +X axis pointed toward magnetic East and +Z axis pointed up.) Due to circumstances beyond control, it was not possible to obtain an accurate survey of receiver locations and orientations with respect to "bench marks" at the time of the tests, so they were simply measured with a tape to the best available physical references.

The transmitting antenna was lowered into the vents using a wire cable attached to the antenna's bail. Two-thousand feet of 2-conductor, 12-gauge "red-line" power cable was spliced to the antenna connector pigtail and periodically secured to the wireline, for support, during descent. At Vent #1, the emergency man hoist was used to lower the antenna. At the unfinished Vent #5, the cable was payed out on the ground and attached to a truck. When the approximate operating depth was reached, the cable was marked in measured 10- or 20-foot (probably to a couple inch accuracy) increments for controlling the distance between measurement stations. Thus, the transmitting antenna measurement station locations (Z axis position) used for data recording are only relative and are not intended to indicate absolute elevation.

Rigidly attached fiberglass strap centralizers were used to keep the antenna from direct contact with the vent walls but the roughly 32-inch (or less) overall diameter they provided was not large enough to guarantee exact centering in the five-foot diameter shafts. It was not practical to realize a large loop structure for these trials, and other structures were ruled out for fear of hanging up or "sailing" in the natural convection airflow that was estimated to be on the order of 20,000 cfm or about 10 mph in Vent #1. (Vent #5 was filled with an estimated 800 to 1000 feet of water.) Thus, the resulting ±1-1/4 foot or so uncertainty in antenna position must be considered when comparing the measured data with the maps. In addition, the vents can "drift" on the order of 10 feet (Vent #5 was 8 feet) between the top and bottom so it was hoped the 50-pound antenna weight would be sufficient to hold it steady and reasonably vertical even if the centralizer was touching the walls. It is important to note that the only time the antenna was observed, from a distance at the bottom of

Vent #1, it appeared fairly well centered (within a couple feet) and relatively steady although conditions could have been different at higher elevations.

4.2 DEMONSTRATION TEST RESULTS AT VENT #1. 1-4 HAULAGE DRIFT

The overall layout of the receiver setup at Vent #1, in the 1-4 haulage drift near the lumber yard, is shown in Figure 7. The receiver station was plotted on the map from measurements made with respect to the vent casing as summarized in Appendix I. The receiver location measurements, relative to the tunnel wall, were made on the next day by carefully re-setting up the magnetometer and measuring its position and orientation. Because the vent alcove door was blocked at the time of the locator measurements, K-M personnel measured the incremental distance from the door to casing at a later date.

The temperature at the receiver location was about 64°F (19°C) and the humidity was relatively low. The surface temperature was on the order of 75°F to 85°F so the relative phase drift between the independently crystal controlled transmitter and receiver was reasonable. Although there was a stiff breeze blowing (estimated at 10 mph) there was no evidence of wind induced noise even at 2 Hz, so shielding was not considered necessary. In fact, a rough noise check made with 0.5 Hz bandwidth and a system gain of approximately 110 dB resulted in a receiver noise output of about ±.7 V peak at 2 Hz, or an equivalent of 3.15 μA/m rms in a .025 Hz BW, which indicates the system was limited by magnetometer noise. There were no indications of powerline or other sources of electrical noise although this was under quiescent weekend conditions and can't be considered typical. Thus, the measurements were made at .025 Hz bandwidth and 2 Hz center frequency to minimize casing attenuation effects and realize a maximum signal-to-noise ratio.

The detail receiver output data is given in Appendix I and the horizontal and vertical magnetic field output levels are plotted in Figure 8. Since this shaft continued on down for another 200 feet or so, the transmitter was lowered an estimated 100 feet below the assumed receiver elevation and then raised in 10-foot increments to get sufficient resolution for the relatively short range. The measurements were terminated when the transmitter antenna was an estimated 60 feet above the receiver, and shortly after the required vertical magnetic field zero crossing was observed, in order to make the man hoist operating schedule.

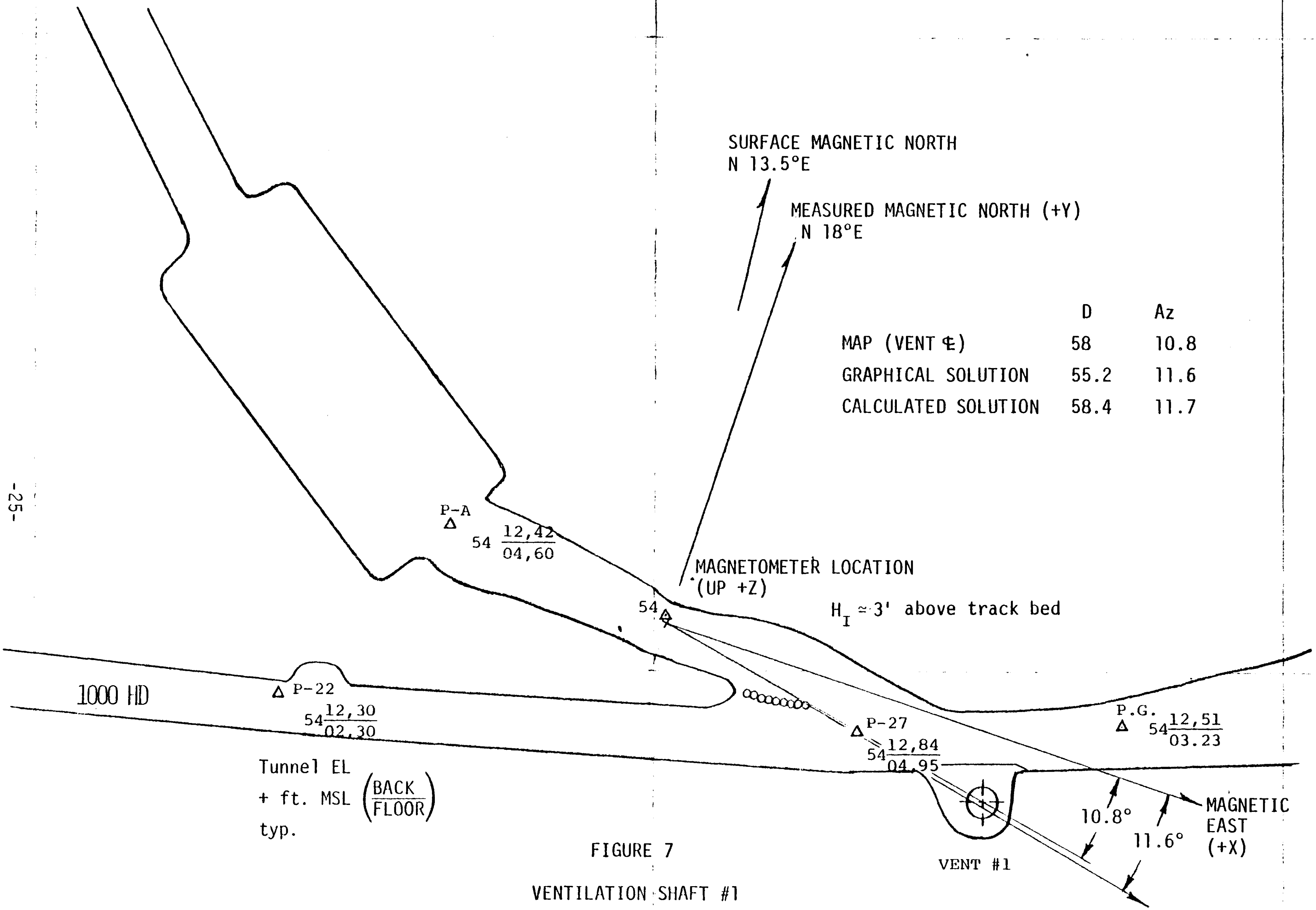


FIGURE 7

VENTILATION SHAFT #1
1-4 Haulage Drift
LAYOUT

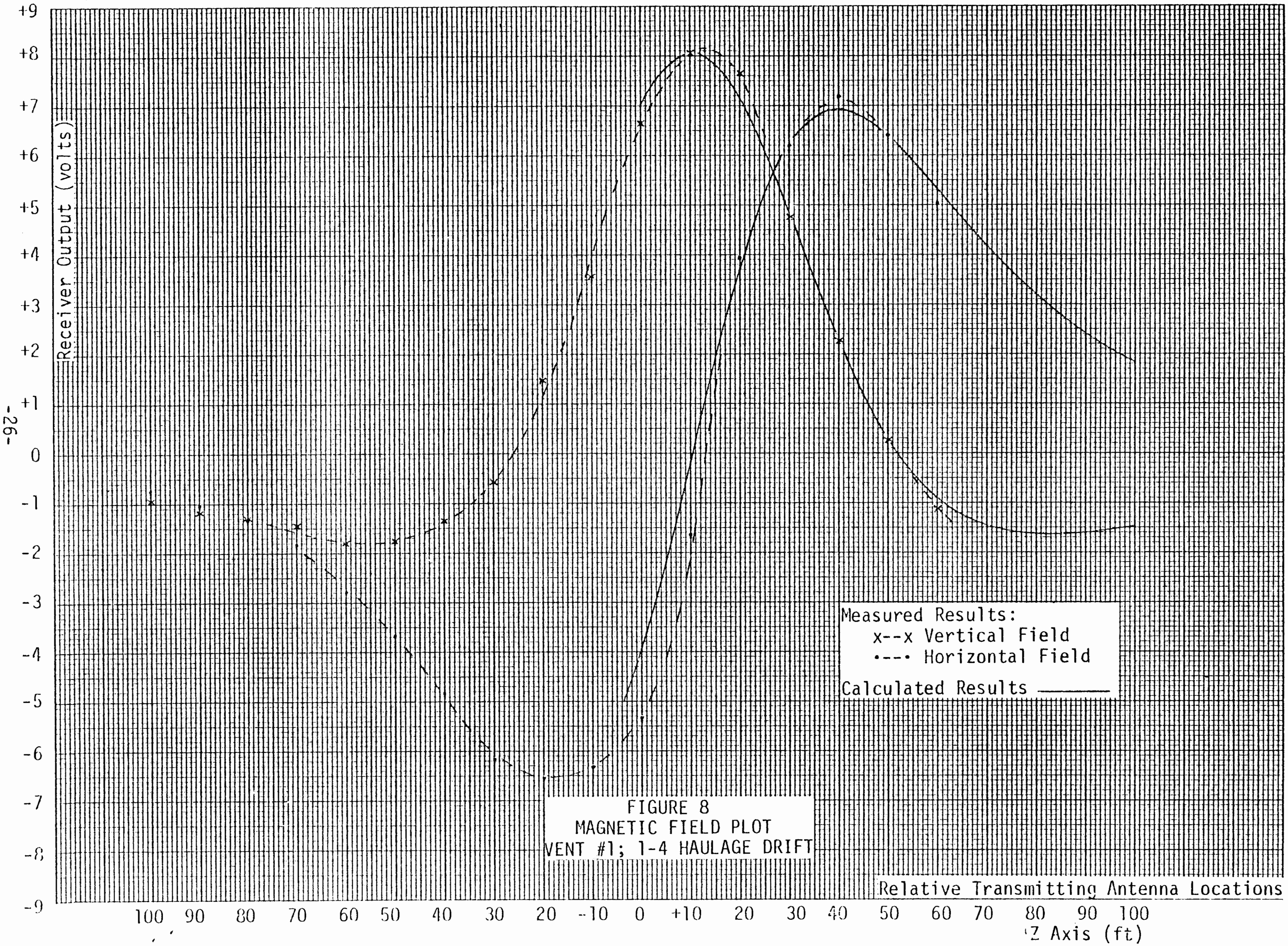


FIGURE 8
MAGNETIC FIELD PLOT
VENT #1; 1-4 HAULAGE DRIFT

The horizontal range from the receiver to the antenna can be estimated by dividing $\sqrt{2}$ into the distance between the two vertical field zeroes on the graph, or 78 feet, which gives D = 55.2 feet (reference Section 2.1). The original estimate, made from a crude graph in the field, was 53 feet. This is only in fair agreement with the value of 58 feet scaled from the map even after allowing for some uncertainty of the antenna position inside the vent. From the graph it can be seen that although the horizontal field zero (which theoretically occurs when the vertical antenna center is at the receiver elevation) is symmetrically located between the others, the amplitude at + and - antenna elevations is not symmetrical. Since the graphical method requires a fairly uniform response to be accurate, this distortion was undoubtedly the major source of error. (Probable causes are discussed more fully below and in Section 4.6.) It may be possible to get a more accurate result from the same data, as discussed in Section 4.5, but this is a good example of the graphical method's limitations in a real world environment.

Since it was not possible to observe the casing, it is not clear what the exact cause of the apparent change in signal characteristics above and below the tunnel was. It may be due to a change in casing attenuation resulting from a change in casing thickness (which is thought not to occur until another 200 feet higher) or electrical properties, other structures in the path, antenna tilt from vertical caused by the borehole drift, or an actual shift of the relative antenna location in the hole since several feet of relative antenna motion was possible even though it was expected to hang fairly straight. It is known there is a cutout in the casing for venting at the drift elevation which, judging from one example observed later, is probably relatively large, i.e., on the order of 6 to 10 feet high. This would tend to distort the field at within 10 to 20 feet of the receiver elevation but should not affect the overall result in this case where a complete set of data above and below the receiver is available. Thus, the most likely causes are changes in casing attenuation or relative position.

The measured results for the bearing from the receiver to the antenna are in much better agreement with the map, Figure 7. This is to be expected since the angle is independent of amplitude variations (assuming isotropy) and ac magnetic fields are relatively undistorted by steel structures. For the purposes of the simple graphical analysis, the bearing is usually obtained from the angle between the X and Y magnetometer output components at or near the horizontal field maximum and vertical field zero since the resolution is best and the results are not significantly affected by any antenna tilt that may occur (see Sections 2.1 and 4.6). In this case the maximum occuring at the higher antenna elevations was used simply because the graphical data appeared to be more uniform (which is not necessarily conclusive). From Appendix I, the bearing angle measured at this point is seen to be 11.6° and the quadrant is S(-Y) of E(+X) based on the relative electrical phase of the components (see Section 2.1).

There is an uncertainty of about .5° in the measurement of the receiver coordinate orientation (see Appendix I), and possibly slightly more from the subsequent casing location measurement. Therefore the minimum has been used in plotting bearing on the map, Figure 7, since it illustrates a worst case result - a larger physical angle between the receiver and vent axis would put the bearing closer to the vent center. From Appendix I, it can be seen that the measured bearing angle for most transmitting antenna locations is fairly uniform. The 5.8° value is clearly a bad value and can be discounted so the overall average is about 11.7° which is in good agreement with the value used. The maximum value is 12.1° and would not result in any significant change in estimated position. Thus the bearing estimate appears to be accurate to within ±.5° and certainly no more than ±1° and is entirely consistent with the relatively crude orientation measurements and the uncertainty of antenna position in the vent.

4.3 DEMONSTRATION TEST RESULTS AT VENT #1. 1-5 HAULAGE DRIFT

These measurements were also conducted at Vent #1 but about 130 feet below the previous station, in a blind location near a training school facility off the 1-5 haulage drift, as shown in Figure 9. Again, the receiver station is plotted on the map from tape measurements with respect to convenient reference points (see Appendix II) but this time without any line of sight "advantage." It was not possible to obtain a receiver axis orientation measurement, due to time constraints, so Kerr-McGee personnel went back some time later and measured the direction of local magnetic North at the same position and instrument height. It is believed this should be quite reproducible because all structures are fixed as shown in the photograph (Figure 6), and this seems to be the case, judging from the results.

The temperature at this receiver location was about 74°F (24°C) and the humidity was relatively high which started to have a small effect on receiver offsets. There were no specific noise measurements, but the receiver signals were about the same as before so the system was probably still magnetometer noise limited. The measurements were again made at .025 Hz bandwidth and 2 Hz center frequency.

Since the shaft could be observed through a hole in the vent alcove baffle, the antenna was lowered until it was just off the bottom. It appeared to hang free, was roughly centered (within a couple of feet) and apparently steady. The vent had a very large cutout (about 3 or 4 feet wide, but the height could not be determined) on the backside (away from the receiver) which undoubtly contributed to the "bottom effects" in the data. The shaft bottom appeared to be concrete lined and a couple feet higher than the tunnel floor. There was very little time for measurements, because of the need to check and secure the vent shaft before the end of the day, so the antenna was moved in 20-foot increments until the vertical magnetic field zero crossing could be resolved.

The detail receiver output data is given in Appendix II and the horizontal and vertical magnetic field output levels are plotted in Figure 10. In this plot the data is seen to be distorted and somewhat inconsistent.

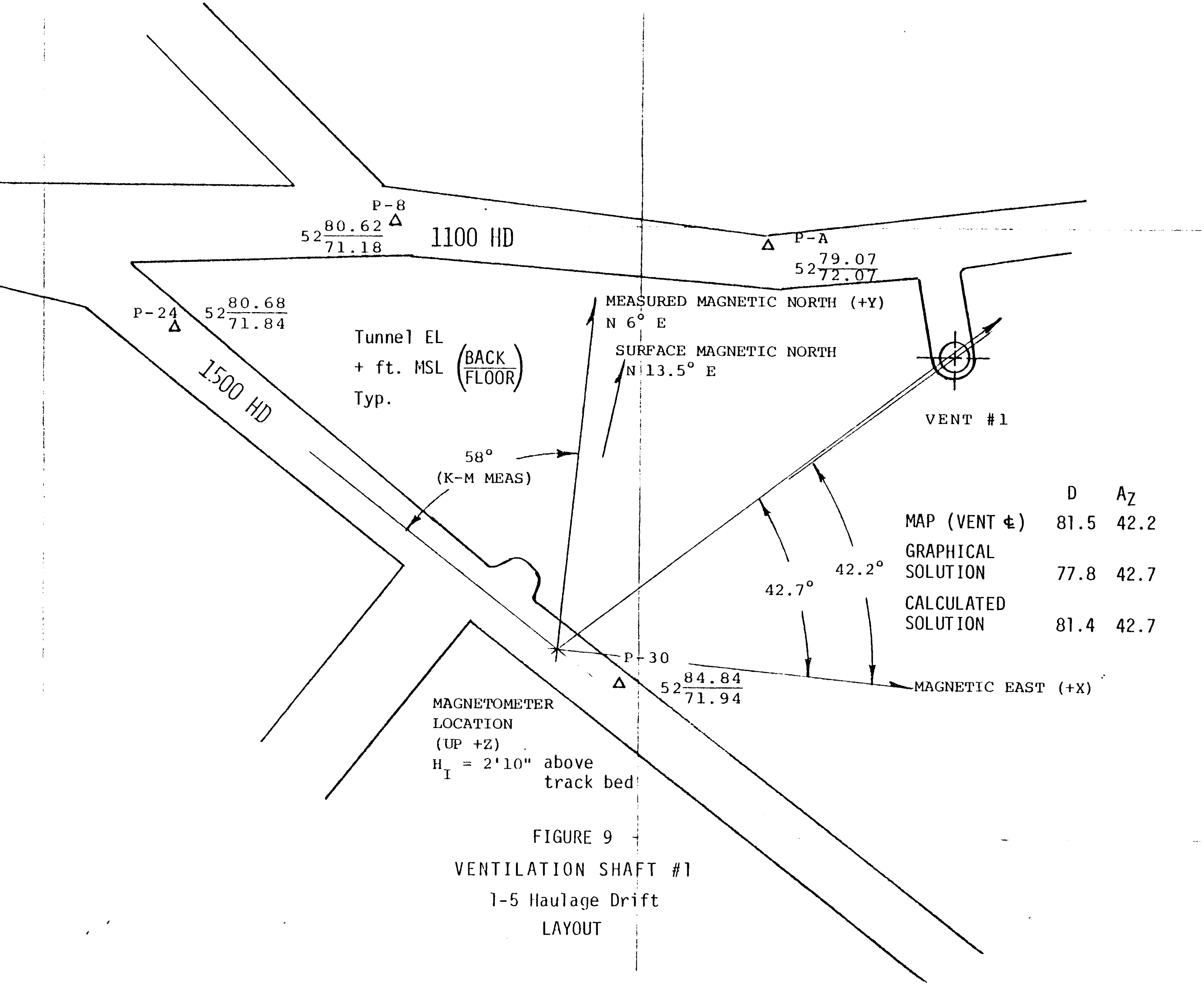


FIGURE 9

VENTILATION SHAFT #1

1-5 Haulage Drift

LAYOUT

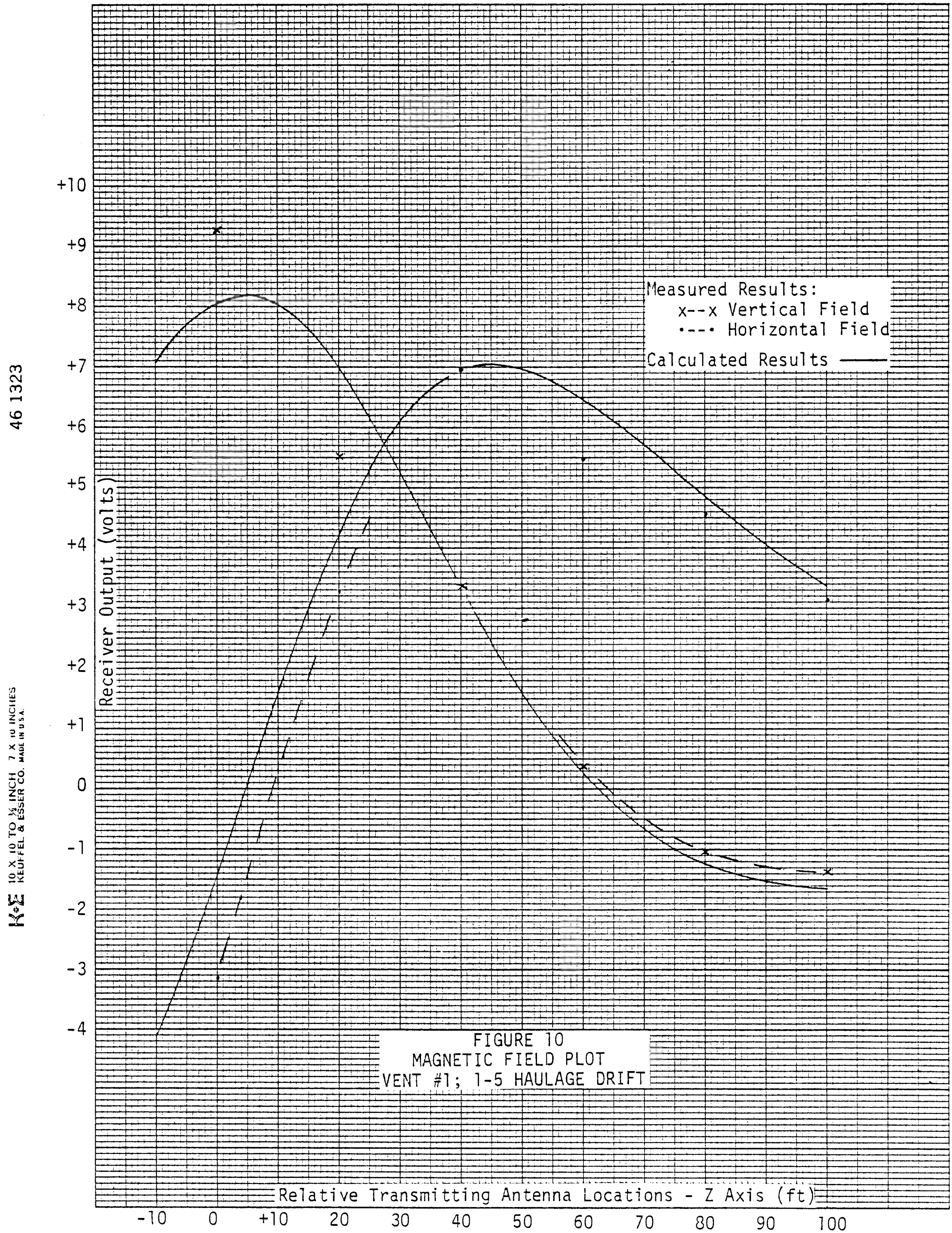


FIGURE 10
MAGNETIC FIELD PLOT
VENT #1; 1-5 HAULAGE DRIFT

Part of this is a result of the lack of resolution due to widely spaced antenna stations. However, the rapid reduction of attenuation near the bottom, due to the cutout and open end, is probably the most significant factor. It results in relatively higher signal levels near zero elevation and gives an inaccurate impression of the zero crossing location. By extrapolating the data points as indicated, the apparent distance between the horizontal and vertical zero crossings is 55 feet and the apparent horizontal range to the antenna axis is $\sqrt{2}$ times that, or 77.8 feet (see Section 2.1). The original rough field estimate was 79 feet. This is not too far off from the 81.5 feet scaled from the map and is a reasonable first estimate although Section 4.5 suggests a more accurate result can be obtained from the same data.

By using the data from near the horizontal field maximum (Appendix II), as in the previous case, the bearing angle is estimated to be 42.7° and the quadrant is N(+Y) of E(+X) based on the relative electrical phase of the components (see Section 2.1). This is in very good agreement with the angle of 42.2° to the vent center scaled from the map and is consistent with the possible actual location of the antenna in the shaft. From Appendix II it can be seen that the measured bearing angle for most antenna locations is again fairly uniform. The value of 47.5° at "+20" could have resulted from incorrect data recording so if it is discounted the overall average is 42.0° with a ±.7° variation. Since the Kerr-McGee measurement of magnetic North is probably accurate to better than 0.5°, the bearing estimate appears accurate to within ±1° and is consistent with the uncertainty of antenna position in the vent.

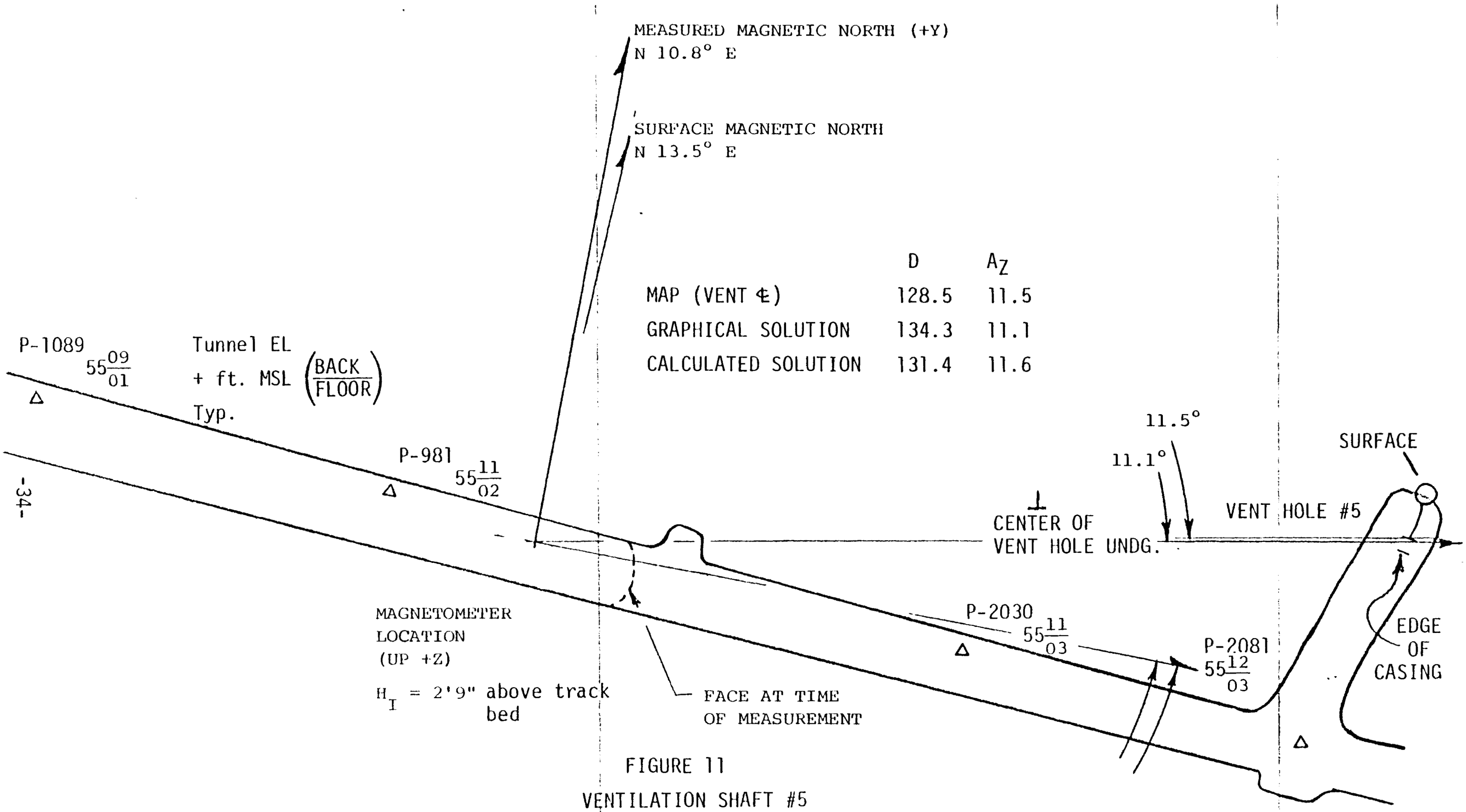
4.4 DEMONSTRATION TEST RESULTS AT VENT #5. 1-4 HAULAGE DRIFT

The receiver was located near the working face of the new tunnel being constructed to connect with Vent #5 as shown in Figure 11. Its orientation was measured with respect to the tracks as shown in Appendix III. In this case, the location along the tunnel was later accurately measured with respect to survey station P-1089 by Kerr-McGee personnel. An attempt to recheck magnetic North with respect to the tracks was not successful, apparently because the tracks had been advanced another 40 feet by the time the measurement was attempted.

The temperature in this area was about 84°F (29°C) and the humidity was extremely high (probably 99%) because of the poor air flow (surface temperature was about 74°F). The protection of the crude demonstration equipment proved to be inadequate for these conditions and the receiver had to be taken to an area with better ventilation, sprayed with demoisturant and sealed with tape. After this the receiver offsets returned to nearly normal values and operated satisfactorily. Again, there were no specific noise measurements but noise levels appeared to be about the same as for the first case, i.e., magnetometer limited, which would be expected because ambient noise was probably even lower than before. These measurements were also made at 0.025 Hz bandwidth and 2 Hz center frequency.

The detailed receiver output data is given in Appendix III and the horizontal and vertical magnetic field output levels are plotted in Figure 12.

The bottom of the new ventilation shaft is nearly the same as that of the tunnel. Since there was no convenient communication with the surface, the antenna was lowered far enough to be sure it was on the bottom, then raised in scheduled increments at predetermined times. However, it can be seen from Figure 12 that there was no signal change until about 40 to 50 feet of cable was pulled out. This indicated that the antenna had hung up (and tilted) at an elevation of about 25 feet above the receiver, on some "junk" that was known to have been dropped in the hole. The subsequent data is very uniform and consistent, possibly because



	D	A_Z
MAP (VENT ℄)	128.5	11.5
GRAPHICAL SOLUTION	134.3	11.1
CALCULATED SOLUTION	131.4	11.6

FIGURE 11
VENTILATION SHAFT #5
1-4 Haulage Drift
LAYOUT

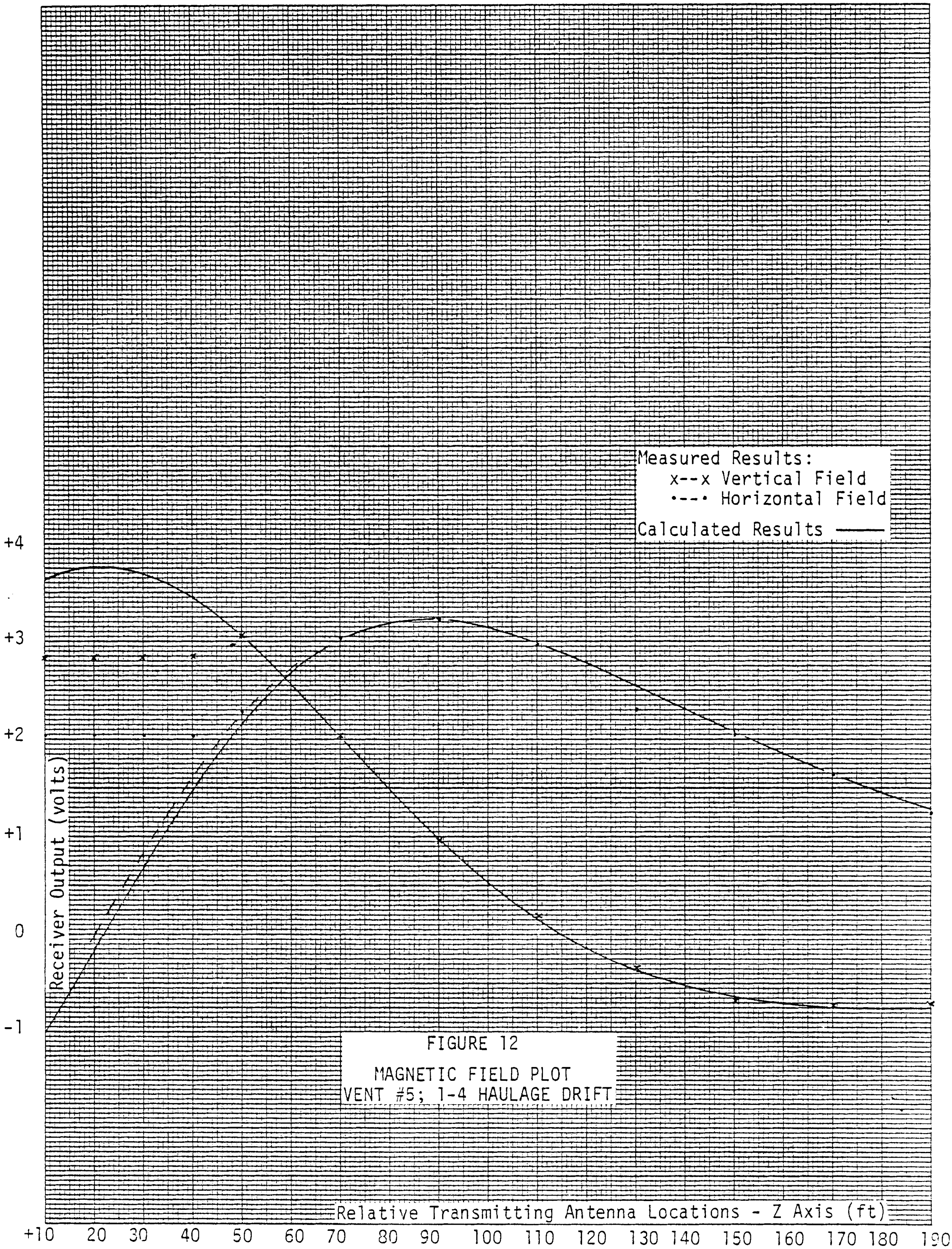


FIGURE 12

MAGNETIC FIELD PLOT
VENT #5; 1-4 HAULAGE DRIFT

antenna motion was damped better in this water-filled hole. (The anomolous point at +130 is possibly due to a local increase in attenuation at that level.)

Although there is some chance the antenna orientation was still not perfectly vertical at the +50 location, this point appears reasonably consistent on the graph and was included in the extrapolation to determine the horizontal field zero crossing. This results in a distance between zero crossings of 95 feet and an apparent horizontal range to the antenna axis $\sqrt{2}$ times that or 134.3 feet (see Section 2.1). The original field estimate was 130 feet based on a rough plot. The distance scaled from the map is 128.5 feet and the difference is probably because the +50 data is slightly in error as suggested by the fact that the bearing result at this point is significantly off (see Appendix III). Again, the analysis in Section 4.5 suggests a more accurate result can be calculated.

Using the data from near the horizontal field maximum (Appendix III), as in the previous cases, the bearing angle to the antenna axis is estimated to be 11.1° and the quadrant is N(+Y) of E(+X) based on the relative electrical phase of the components (see Section 2.1). From Appendix III, the average bearing angle of all data points, except +50, is 11.5° and the variation is +.7° and -1.2°. Since the magnetometer orientation accuracy is estimated to be better than 0.5°, the bearing estimate is probably accurate to on the order of ±1° or about twice that which can be attributed to antenna position uncertainty. In any case, the bearing is again in very good agreement with the map.

4.5 CALCULATED RESULTS

In order to check the consistency and overall accuracy of the data obtained in these measurements a series of calculations was done using the procedures developed for the horizontal drilling application described in Appendix IV. While the results of this preliminary analysis cannot be considered conclusive, because many subjective decisions were involved, there was a consistent tendency to converge on answers that were in agreement with the map and near or within the limits of antenna position uncertainty. The primary value of this exercise was in achieving a general understanding of the factors which affect the field measurements under real conditions and in conceiving procedures for improving the accuracy of the method.

The data analysis consisted of using an iterative type calculation which finds the best theoretical fit with up to 6 data points. By running 3 or 4 cases, the probable erroneous data points could be identified and the theoretical case producing the lowest error, i.e., the best fit with the final data points used, was determined. The general criteria used in determining "bad" data points to be avoided in the calculation were significant inconsistencies in the horizontal and vertical field strengths, or bearing angle or results that were in gross disagreement with the map. In addition, data points in the immediate vicinity of the Vent #1 openings were avoided. The final theoretical curves that resulted are plotted as the solid lines in Figures 8, 10 and 12. The calculated range and azimuth that are consistent with these curves are tabulated in Figures 7, 9 and 11.

Three separate cases were calculated using the data for Vent #1 at the 1-4 level. The first used arbitrarily selected data at + and - antenna elevations (relative to the receiver) and resulted in a curve that was in fair agreement with the data overall and matched the + elevations best.

The average error* between the data and theoretical curve was 7.8%, the calculated range was 57.8 feet and azimuth was 11.6°. Since there was a clear difference between the (+) and (-) elevation results, the next case used only (-) elevation data points. The final average error was 4.7%, range was 59.1 feet, and azimuth was 11.9°. However, while the curve fit with (-) elevation points was better, it still wasn't good, which indicated data inconsistencies possibly due to shifts in relative antenna position. Next, only (+) elevation points (except 10 and 20) were used which resulted in an average error of 2.6% and the best general fit with (+) elevation data as shown in Figure 8. Although the irregularity at +40 feet is not understood, the calculated range and bearing of 58.4 feet and 11.7° is in general agreement with the other results.

The results of the calculations for Vent #1 at the 1-5 level were not quite as good, probably because there were so few data points, but the answers were within reason. By using the data points at +40, 80 and 100, which seemed to be the most consistent, an average error of 4.6% was obtained for a calculated range and azimuth of 81.4 feet and 42.7°. This is very close to the results scaled from the map. The theoretical curve calculated for this case, plotted in Figure 10, clearly illustrates the distortion at the bottom resulting from the large cutout, etc. At the +20-foot point there was variation in bearing angle and amplitude that may have resulted from antenna tilt if it first contacted the vent walls in this region. The relatively lower amplitude values that occured at +60 may have been due to a local increase in casing attenuation.

The best theoretical fit with the data was obtained for Vent #5 as shown in Figure 12. This may have resulted from the fact that antenna motion was much better damped by being under water as mentioned earlier.

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*The average error is defined in terms of the 3 dimensional magnetic field vector, and is the sum of the differences between the data and theoretical amplitudes divided by the sum of the theoretical amplitudes for the data points used in the calculation.

By eliminating the data at +50, which still did not appear normal although ascent had started, and at +130, which was singularly inconsistent, a result with an average error of 1.5% was obtained. The calculated range for this case was 131.4 feet and the bearing was 11.6°. Although the range is slightly in excess of that which could possibly be attributed to antenna location certainty, it is still in good agreement with the map in terms of percent of range. The bearing is in good agreement with the other values.

In conclusion, the discrepancies between the various theoretical cases and the actual data was not great and was generally consistent with antenna position uncertainty. This indicated a convergence on answers that were real and not coincidental which suggests that procedures can be developed to first limit data requirements then automatically select the best points to produce the most accurate results.

4.6 ERROR DISCUSSION

The primary sources of error in the relatively simple demonstration of the hole location technique, described above, are:

1. Uncertainty of antenna location in the borehole because of
   a) The small centralizer used which resulted in a general position uncertainty of ±1.5 feet.
   b) The vertical ventilation shaft drift of about 0.3° which could result in 0.5 foot displacement in 100 feet of travel if followed directly.
   c) Sudden changes in relative antenna position (either large tilt or lateral displacement) caused by wind, antenna or cable contact with the casing walls or irregularities, etc.
   d) Errors in measuring vertical antenna station position.

2. Receiver station location surveying errors which could easily be on the order of 0.5° to 1° and 1 foot considering that all positions were established from several measurements by different people. (Includes errors in positioning receiver with respect to North and vertical.)

3. Nonuniform signal response from different transmitting antenna stations due to such causes as
   a) Openings in the casing walls or at the bottom itself.
   b) Variations in expected range due to shifts of relative position in the casing (see 1).
   c) Local increases in attenuation due to unknown structures on the casing itself or in the direct path to the receiver.

4. Noisy signals due to electrical (e.g., the magnetometer) or mechanical (e.g., wind) variations that limited resolution.

5. Map scaling inaccuracies up to 1 foot and 0.25° because of paper stretch and the small scale used which limited data comparison.

6. Limitations of the graphical method because of geometric distortions or lack of sufficient data.

7. Limitations of the calculation methods because of possible errors in choosing the "correct" (uniformly consistent) data points.

It was beyond the scope of this program to perform a detail error analysis or conduct a rigorously controlled system calibration experiment. Thus a definitive statement of the locator method's inherent accuracy limits cannot be made at this time. However, the fact that such consistent results were obtained in all three cases suggests they can be fairly used to indicate performance capability since the uniformity is unlikely to be coincidental and there were no known sources of large systematic errors.

Therefore, we would estimate that a fairly simple system used in somewhat uncertain conditions (e.g., reasonable position unknowns, casing variation unknowns, etc.) should be able to achieve range accuracies of a couple feet to ±5%, for ranges of greater than 100 feet, when using the graphical solution, and bearing accuracies of better than ±1°. The accuracy can probably be readily improved to on the order of less than 1 or 2% of range and ±.5° of bearing angle by making even simple improvements such as precisely orienting the antenna in the hole and measuring receiver location, taking more data points or knowing more about the casing structure. The horizontal drilling experience, described in Appendix IV, suggests that range and bearing accuracies of better than one-half percent and a few tenths of one degree, respectively, can be achieved by using a more elaborate approach such as two receiver stations and computer calculations. The latter approach would have the added advantage of being able to compute borehole tilt which can be on the order of 5° in some situations.

5. CONCLUSIONS AND RECOMMENDATIONS

The feasibility tests of the borehole location concept described in this report have shown that

1. Location of cased, as well as uncased, holes can be achieved so the method will be useful in a wide variety of mine applications.

2. Accuracy is not significantly affected by the variety of potentially disturbing influences commonly found in mines such as steel structures, tracks, power lines, etc.

3. Very reasonable accuracy (range $<\pm 5\%$, bearing $<\pm 1°$) can be achieved with a relatively simple system and crude setups which makes it inherently suitable for use in a mine environment.

4. Considerably improved accuracy (range $<\pm 2\%$, bearing $<\pm .5°$) can be achieved with the same basic method using refined techniques which would make it a very useful aid for more general and precise mine surveying work.

The operating range of the test system is estimated to be on the order of 150 to 200 feet with casing attenuations of about 6 dB, as encountered in the actual measurements, which appears useful for many applications. If the casing attenuation is on the order of a couple dB, which would be typical of smaller diameter holes and/or thinner casings, the same system would be capable of satisfactory operation at ranges of 250 to 300 feet or more. By using a larger antenna and/or a more sensitive receiver, accurate operation at considerably longer ranges is conceivable. Thus, the ability to make blind measurements of range with fair accuracy could be a valuable aid in general surveying work, when the potentially more accurate conventional methods are very difficult to use, as well as in hole locator work where it is the only satisfactory way to make a direct measurement.

The high accuracy of the bearing measurements, while not entirely unexpected, was surprisingly immune to effects from the variety of the steel structures found in the mine and this may be of considerable value in itself. The measured values of local magnetic north varied as much as 12° between the three measurement locations which represents a very large error for any survey work that attempts to use magnetic measurements. (The nominal value of magnetic north at the mine location is approximately N13.5°E). Because it is so simple to determine, bearing might also provide a much quicker but accurate fix on location when circumstances permit, as in the original Bureau of Mines trials, or as a quick check as tunneling progresses towards a target.

It is clear that the locator concept has technical merit and potential advantages in some obvious mine applications. In addition, like any successful new tool, it is conceivable that it may generate many new applications. However, its success and acceptance will depend more on the ability to demonstrate significant cost savings, for mines, than on its technical advantages or ease of use.

It is possible to get some idea of the cost advantages by considering its use as a locator alone. For example, in one known instance, a vent shaft was more than 10 feet off from its predicted location and 1 week was spent probing for it at a direct cost of approximately $1600. In this case, it was dead ahead instead of in the right rib which required reworking the haulage drift. Thus, by including the rework, additional surveying effort, lost operating time, etc., it is likely the total extra cost of the hole location problem was in excess of 3 times the direct cost or on the order of $6000 or more. While this is probably an extreme case, and there are others that are no problem at all, it seems that there are enough hole location problems in general to assume that there is an average extra cost of $2000 per hole as a result of the uncertainties involved. It is reasonable to assume a location measurement could be supplied by an outside service company for on the order of $1000 per operation, including equipment amortization, crew costs and expenses.

In the Grants Mining district of New Mexico, which is composed of Church Rock, Ambrosia Lakes and Crown Point, there are approximately 15 mines in operation now and a possibility of 30 by 1985. If the locator service is priced right, a typical mine might have a use for it as much as 5 or 6 times a year during development phases. A total use of 20 times per year in the district is probably a conservative minimum average in the near term. Thus, it seems reasonable to estimate that some mines could easily realize an annual savings of $2000-$6000 and the annual market for the service in the district is on the order of at least $20,000 for this service alone.

There are other factors to be considered too. As mines go deeper (e.g., 3000 feet), hole drifts get greater and operating costs go up, so the potential savings are probably significantly greater. In addition, lost operating time due to schedule delays, construction, and structural problems because too much ground is opened up and so on, are things which are very difficult to cost estimate but may be very important. The hole locator might also replace the need for, or be combined with, hole deviation and bottom surveys in some or all applications, depending on the mix of exploratory and service holes, which would result in additional direct cost savings. Thus, it would seem that when all things are considered, the cost advantages would certainly be of interest to mine operators if the locator service were available, even though it is not yet totally clear whether the potential hole locator market alone is large enough to justify development.

However, it is very possible that the same techniques, and perhaps even much of the same hardware, are applicable to a sufficient variety of other mining problems to materially enhance the incentives to develop and use them. The use as a blind surveying aid for general work and as a substitute for, or in conjunction with, hole deviation surveys has already been mentioned. It is also conceivable that the methods can be applied to continuous surveying and navigation in the relatively shallow (up to a couple thousand feet) mine drilling problems such as raise bore pilot hole control, deviated drilling for methane drainage, or ore body target verification in exploratory work. Other possible navigation applications include use as a target in drilling holes from the surface into existing tunnels (e.g., rescue) or driving a tunnel to a critical intersection.

In summary, it appears that there are a sufficient number of technically and economically important applications to warrant further market investigation and instrumentation development.

REFERENCES

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2. Richard M. Bozorth, Ferromagnetism, D. Van Nostrand Company Inc., Princeton, New Jersey, 1951.

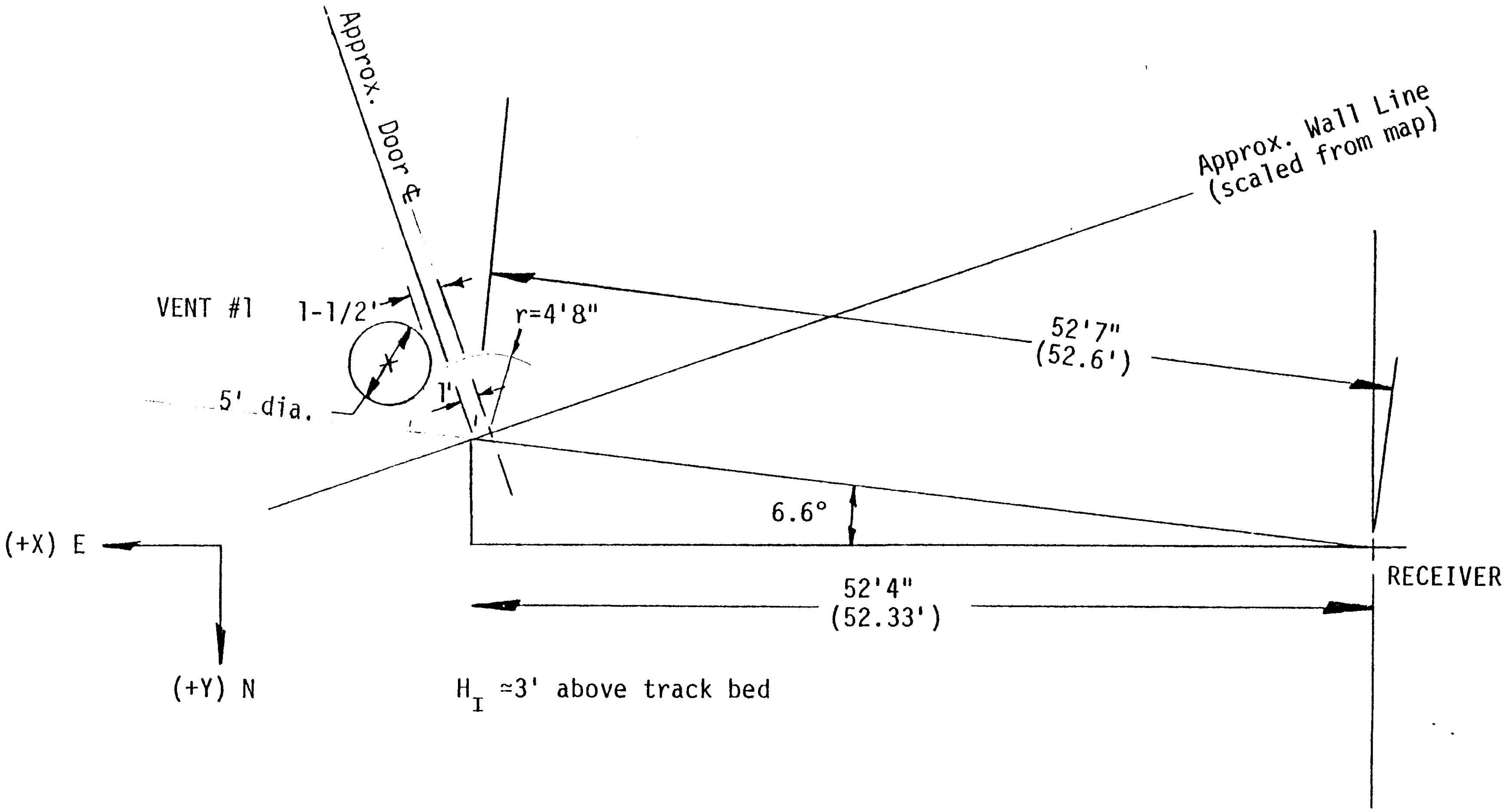
3. Saul Shenfield, Shielding of Cylindrical Tubes, IEEE Transactions on Electromagnetic Compatibility, Vol. EMC-10, No. 1, March 1968.

4. W.D. Bensama, Coal Mine ELF Electromagnetic Noise Measurement, NBS Report 10-739, April 1972.

5. This is a commonly used expression in geophysical work for evaluating noise data and is based on the fact that a gaussian distribution exceeds $\pm 2.5\sigma$ about 1% of the time.

APPENDIX I

MEASURED DATA AT VENT #1/1-4 HAULAGE DRIFT



#1 VENT/1-4 LEVEL SURVEY SUMMARY

APPENDIX I

DATA SUMMARY

VENT # 1 ; 1-4 HAULAGE DRIFT

RECEIVER ORIENTED +Z UP; +Y NORTH

TRANSMITTER f = 2 Hz; RECEIVER BW ≃.025 Hz

GAIN SETTINGS: Preamp (nom) 68 dB
"RF" 0 dB
Detector 10 dB

Z (FT)		I (V)	Q (V)	$\lvert V\rvert$ (V)	$\tan^{-1}\frac{Q}{I}$ (deg)	$\lvert V_T\rvert$ (V)	$\tan^{-1}\frac{Y}{X}$ (deg)	DIRECTION
-100	X	+ .01	- .74	.74	-89.2			
	Y	- .02	+ .15	.15	-82.4	.76	11.46	
	Z	- .03	+ .93	.93	-88.2			
-90	X	.00	-1.02	1.02	-90.0			
	Y	- .03	+ .18	.18	-80.5	1.04	10.01	
	Z	.00	+1.17	1.17	-90.0			
-80	X	+ .06	-1.33	1.33	-87.4			
	Y	- .03	+ .28	.28	-83.9	1.36	11.89	
	Z	- .09	+1.29	1.29	-86.0			
-70	X	+ .30	-1.78	1.81	-80.4			
	Y	- .08	+ .36	.37	-77.5	1.85	11.55	
	Z	- .25	+1.41	1.43	-79.9			
-60	X	- .23	-2.73	2.74	85.2			
	Y	+ .05	+ .57	.57	85.0	2.80	11.75	
	Z	+ .14	+1.79	1.80	85.5			
-50	X	+ .53	-3.55	3.59	-81.5			
	Y	- .16	+ .73	.75	-77.6	3.67	11.80	
	Z	- .23	+1.74	1.76	-82.5			
-40	X	+ .90	-4.66	4.75	-79.1			
	Y	- .20	+ .98	1.00	-78.5	4.85	11.89	
	Z	- .20	+1.32	1.34	-81.4			
-30	X	+ .93	-5.94	6.01	-81.1			
	Y	- .19	+1.25	1.26	-81.4	6.14	11.84	
	Z	.00	+ .57	.57	-90.0			
-20	X	+2.20	-5.98	6.37	-69.8			
	Y	- .44	+1.30	1.37	-71.3	6.52	12.14	
	Z	+ .64	-1.35	1.49	-64.6			
-10	X	+2.40	-5.69	6.18	-67.1			
	Y	- .45	+1.20	1.28	-69.4	6.31	11.70	
	Z	+1.54	-3.23	3.58	-64.5			

APPENDIX I
(CONTINUED)

DATA SUMMARY

VENT # 1 ; 1-4 HAULAGE DRIFT

GAIN SETTINGS: Preamp (nom) 68 dB
"RF" 0 dB
Detector 10 dB

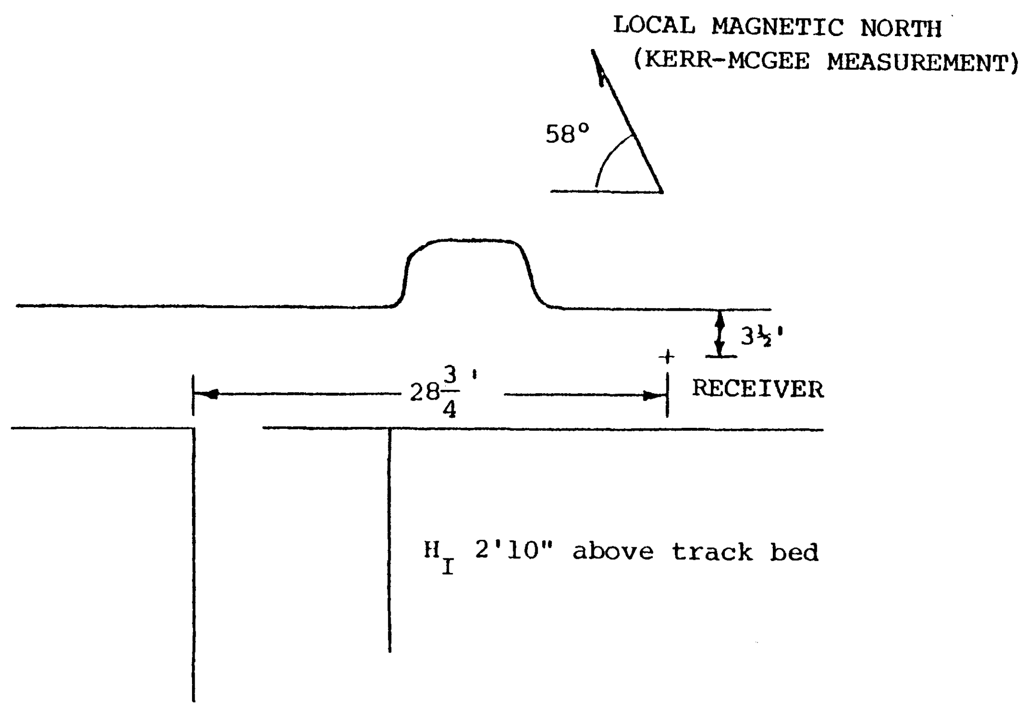
RECEIVER ORIENTED +Z UP; +Y NORTH

TRANSMITTER f = 2 Hz; RECEIVER BW ≈.025 Hz

Z (FT)		I (V)	Q (V)	$\lvert V\rvert$ (V)	$\tan^{-1}\frac{Q}{I}$ (deg)	$\lvert V_T\rvert$ (V)	$\tan^{-1}\frac{Y}{X}$ (deg)	DIRECTION
0	X	+1.83	-4.89	5.22	-69.5			
	Y	- .31	+ .96	1.01	-72.1	5.32	10.95	
	Z	+2.50	-6.15	6.64	-67.9			
+10	X	- .04	-1.63	1.63	88.6			
	Y	+ .29	+ .07	.30	13.5	1.66	10.43	
	Z	+2.12	-7.77	8.05	-74.7			
+20	X	- .84	+3.83	3.92	-77.6			
	Y	+ .15	- .37	.40	-67.9	3.94	5.83	
	Z	+3.25	-6.94	7.66	-64.9			
+30	X	-2.95	+5.32	6.08	-61.0			+
	Y	+ .63	-1.01	1.19	-58.0	6.20	11.07	-
	Z	+2.72	-3.93	4.78	-55.3			Δ +
+40	X	-3.50	+6.13	7.06	-60.3			
	Y	+ .75	-1.24	1.45	-58.8	7.21	11.61	
	Z	+1.37	-1.81	2.27	-52.9			
+50	X	-3.50	+5.20	6.27	-56.1			
	Y	+ .76	-1.08	1.32	-54.9	6.41	11.89	
	Z	+ .27	- .06	.28	-12.5			
+60	X	-2.97	+3.95	4.94	-53.1			
	Y	+ .66	- .84	1.07	-51.8	5.06	12.22	
	Z	- .57	+ .95	1.11	-59.0			

APPENDIX II

MEASURED DATA AT VENT #1/1-5 HAULAGE DRIFT



#1 VENT/1-5 LEVEL SURVEY SUMMARY

APPENDIX II

DATA SUMMARY

VENT # 1 ; 1-5 HAULAGE DRIFT

RECEIVER ORIENTED +Z UP; +Y NORTH

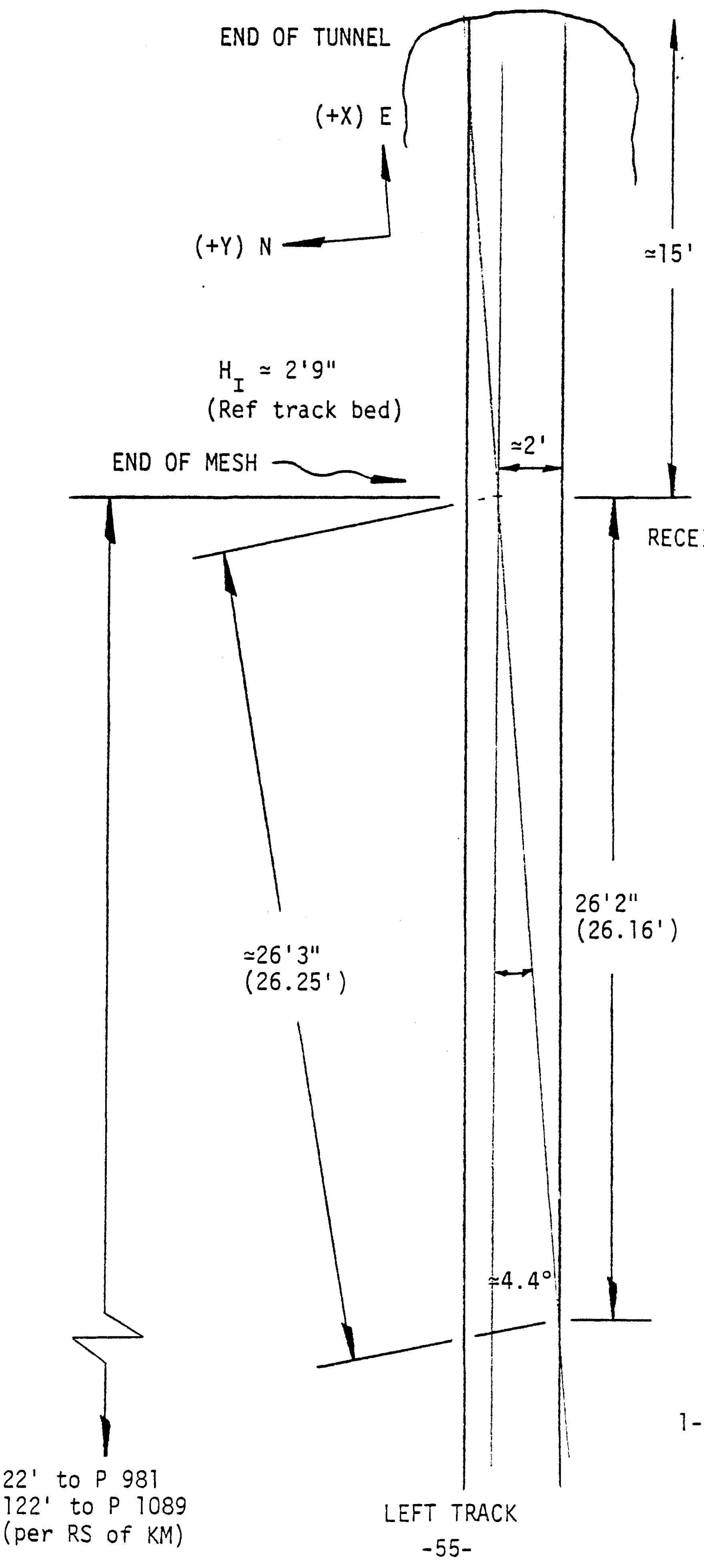
TRANSMITTER f = 2 Hz; RECEIVER BW ≈.025 Hz

GAIN SETTINGS: Preamp (nom) 68 dB
"RF" 10 dB
Detector 10 dB

Z (FT)		I (V)	Q (V)	$\lvert V \rvert$ (V)	$\tan^{-1} \frac{Q}{I}$ (deg)	$\lvert V_T \rvert$ (V)	$\tan^{-1} \frac{Y}{X}$ (deg)	DIRECTION
0	X	-2.18	- .75	2.31	19.0			
	Y	-1.88	- .98	2.12	27.5	3.14	42.54	
	Z	+8.73	+3.18	9.29	20.0			
+20	X	- .49	-2.15	2.21	77.2			
	Y	- .76	-2.29	2.41	71.6	3.27	47.48	
	Z	+2.12	+5.08	5.51	67.3			
+40	X	-1.88	-4.74	5.10	68.4			+
	Y	-1.71	-4.39	4.71	68.7	6.94	42.72	+
	Z	+1.10	+3.14	3.33	70.7			$\triangleq$ +
+60	X	- .60	-4.02	4.07	81.5			
	Y	- .47	-3.62	3.65	82.6	5.47	41.88	
	Z	+ .03	+ .37	.37	85.4			
+80	X	- .30	-3.41	3.42	85.0			
	Y	- .18	-2.99	3.00	86.6	4.55	41.25	
	Z	- .04	-1.02	1.02	87.8			
+100	X	+ .03	-2.34	2.34	-89.98			
	Y	+ .05	-2.06	2.06	-88.6	3.12	41.36	
	Z	+ .04	-1.38	1.38	-88.3			

APPENDIX III

MEASURED DATA AT VENT #5/1-4 HAULAGE DRIFT



#5 VENT
1-4 LEVEL SURVEY SUMMARY

DATA SUMMARY

VENT # 5 ; 1-4 HAULAGE DRIFT

RECEIVER ORIENTED +Z UP; +Y NORTH

TRANSMITTER f = 2 Hz; RECEIVER BW ≈.025 Hz

GAIN SETTINGS: Preamp (nom) 68 dB
"RF" 20 dB
Detector 10 dB

Z (FT)		I* (V)	Q* (V)	$\lvert V \rvert$ (V)	$\tan^{-1}\frac{Q}{I}$ (deg)	$\lvert V_T \rvert$ (V)	$\tan^{-1}\frac{Y}{X}$ (deg)	DIRECTION
+40	X	+1.76	+1.03	2.04	30.3			
	Y	- .05	+ .11	.12	-65.6	2.04	3.37	
	Z	-2.01	-2.02	2.85	45.1			
+50	X	+1.68	+1.48	2.24	41.4			
	Y	+ .23	+ .28	.36	50.6	2.27	9.13	
	Z	-1.90	-2.38	3.05	51.4			
+70	X	+1.77	+2.37	2.96	53.2			
	Y	+ .41	+ .49	.64	50.1	3.03	12.2	
	Z	-1.03	-1.75	2.03	59.5			
+90	X	+1.47	+2.81	3.17	62.4			+
	Y	+ .23	+ .58	.62	68.4	3.23	11.1	+
	Z	- .29	- .90	.95	72.1			Δ +
+110	X	+ .91	+2.76	2.91	71.8			
	Y	+ .12	+ .60	.61	78.7	2.97	11.8	
	Z	- .03	- .19	.19	81.0			
+130	X	+ .31	+2.22	2.24	82.1			
	Y	+ .11	+ .44	.45	76.0	2.28	11.4	
	Z	- .03	+ .36	.36	85.2			
+130 (Rpt)	X	- .26	+2.26	2.28	-83.4			
	Y	- .04	+ .44	.44	-84.8	2.32	10.9	
	Z	- .04	+ .31	.31	-82.6			
+130 (Avg)	X			2.26				
	Y			.45		2.30	11.26	
	Z			.34				
+150	X	- .40	+1.96	2.00	-78.5			
	Y	- .11	+ .41	.43	-75.0	2.05	12.1	
	Z	- .11	+ .66	.67	-80.5			
+170	X	- .64	+1.47	1.60	-66.5			
	Y	- .09	+ .28	.29	-72.2	1.63	10.3	
	Z	- .31	+ .66	.73	-64.8			

*Corrected for offset.

APPENDIX III
(CONTINUED)

DATA SUMMARY

VENT # 5 ; 1-4 HAULAGE DRIFT

GAIN SETTINGS: Preamp (nom) 68 dB
"RF" 20 dB
Detector 10 dB

RECEIVER ORIENTED +Z UP; +Y NORTH

TRANSMITTER f = 2 Hz; RECEIVER BW ≈.025 Hz

Z (FT)		I (V)	Q (V)	$\|V\|$ (V)	$\tan^{-1}\frac{Q}{I}$ (deg)	$\|V_T\|$ (V)	$\tan^{-1}\frac{Y}{X}$ (deg)	DIRECTION
+190	X	- .64	+1.03	1.21	-58.1			
	Y	- .16	+ .19	.25	-49.9	1.24	11.67	
	Z	- .38	+ .60	.71	-57.6			

APPENDIX IV

DEMONSTRATION OF AN ELECTROMAGNETIC NAVIGATION METHOD
ON TITAN CONTRACTORS LARGE BORE DRILLED RIVER CROSSING
AT GREENS BAYOU, HOUSTON, TEXAS

January 1978

ACKNOWLEDGEMENTS

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T.C. Moore
L.H. Rorden

DEMONSTRATION OF AN ELECTROMAGNETIC NAVIGATION METHOD ON TITAN CONTRACTORS LARGE BORE DRILLED RIVER CROSSING AT GREENS BAYOU, HOUSTON, TEXAS

Titan Contractors Corporation of Sacramento, California has developed a means of drilling small bore pipeline crossings under rivers and other similar obstructions that they have been using with a relatively high degree of success for the past several years. Conventional directional measurement techniques had been used which at best were time consuming and at worst led to unacceptable errors, particularly when obstacles exist close to the right of way. This seemed to be an ideal application for using the basic borehole location techniques as a means of navigating a directional drilling operation that might be applicable to such Bureau of Mines problems as the methane drainage program and others. Therefore, arrangements were made to try the locator method on a radically different large bore drilling program that Titan was undertaking in late 1977. The Bureau of Mines technical officer approved the use of the equipment prepared on the borehole locator contract (J0177074). Develco, Inc. supported special equipment design and preparation and the development of calculation programs, and Titan Contractors supported the field measurements in a cooperative effort to demonstrate the feasibility.

The work was successfully completed in early January 1978 when Titan succeeded in drilling a 30-inch diameter casing, for an oil pipeline, along a curved path approximately as shown in Figure 1. It is believed that this is the first time that the directional drilling of such a large bore using a steerable drill bit section has ever been accomplished, particularly in essentially one operation. (Because this was the first field operation of a radically different drill rig, the field work occured in two parts to permit some modifications - this brief account covers the final operation.) The navigation requirements were fairly critical because of drilling operation considerations, the pipeline design parameters, and the existence of a gas line in the adjacent right of way (approximately 15 to 20 feet away at one point). Titan had built conventional magnetic and gravity sensors into the drill section and had planned to supplement this with periodic gyroscope measurements. However, it was expected that magnetic azimuth

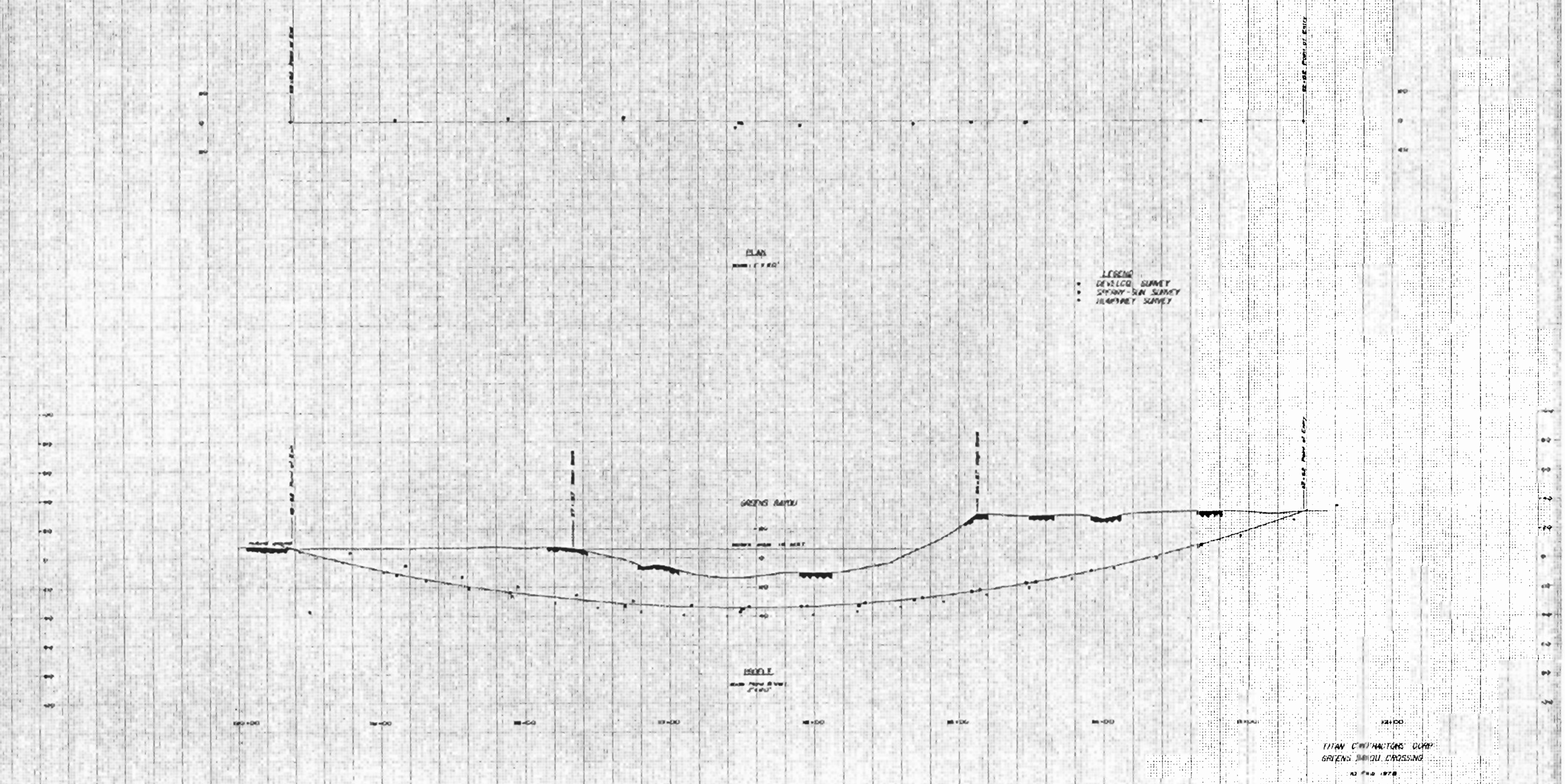

PLAN
LEGEND
DEVELCO SURVEY
SPERRY-SUN SURVEY
HUMPHREY SURVEY
GREENS BAYOU
PROFILE
TITAN CONTRACTORS CORP
GREENS BAYOU CROSSING

FIGURE IV-1

information would be very uncertain because of the presence of nearby pipelines, bridges, railroad tracks, barge traffic, etc., and this proved to be the case. Due to difficulties with the gyros, the locator system was the only source of azimuth information, and provided a valuable cross check on the other data, so the operation turned out to be of more value than a simple demonstration.

The locator antenna was mounted in the drill section, which consisted of a casing with a wall thickness varying from 1/4 to 1/2 inch and various internal machinery, approximately as shown in Figure 2. Preliminary measurements suggested, and later calculations confirmed, that there was relatively little distortion of the transmitted field due to misalignment, the surrounding drill structures or the receiver structure. Rough measurements of signal attenuation made with the antenna at an initial location in the drill resulted in approximate values of 2.5 dB at 2 Hz, 5 dB at 4 Hz, and 10 dB at 8 Hz. The attenuation values were about doubled in the final location, but the signal strengths produced were entirely adequate for the ranges of interest. The antenna drive was essentially the same as in the mines case, i.e., approximately square wave with an amplitude of about ±3A producing a moment of about 1400 $A \cdot m^2$ peak. However, truck batteries were connected to the transmitter power supply to considerably improve amplitude stability.

Measurements of the fields produced at the surface were made at presurveyed stations as shown in Figure 3. Unlike in the borehole locator case, it is the instantaneous transmitter position that is important so measurements of the surface fields were made for at least two receiver locations (and sometimes 3 or 4 for redundancy) at appropriate distances from each transmitter location. This required moving the receiver, since only one was available, and took some time, so measurements were usually made while a casing joint (about 40 feet) was being added. However, it is important to recognize that a high speed automatic measurement system and multiple sensors could achieve real time measurements while drilling. In order to achieve relatively quick setups with considerable alignment accuracy, the magnetometer receiver was mounted on a transit head as shown in Figure 4. (Fairly good results were achieved with a much cruder setup in the initial work, but the refinements greatly improved the system accuracy and made possible the final result discussed below.)

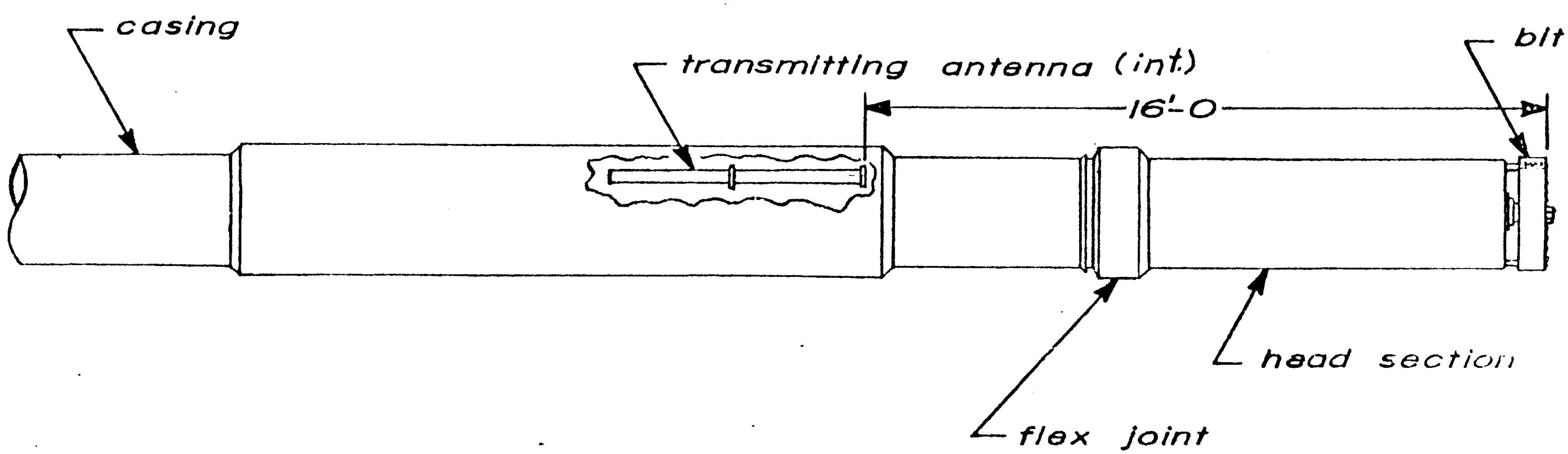


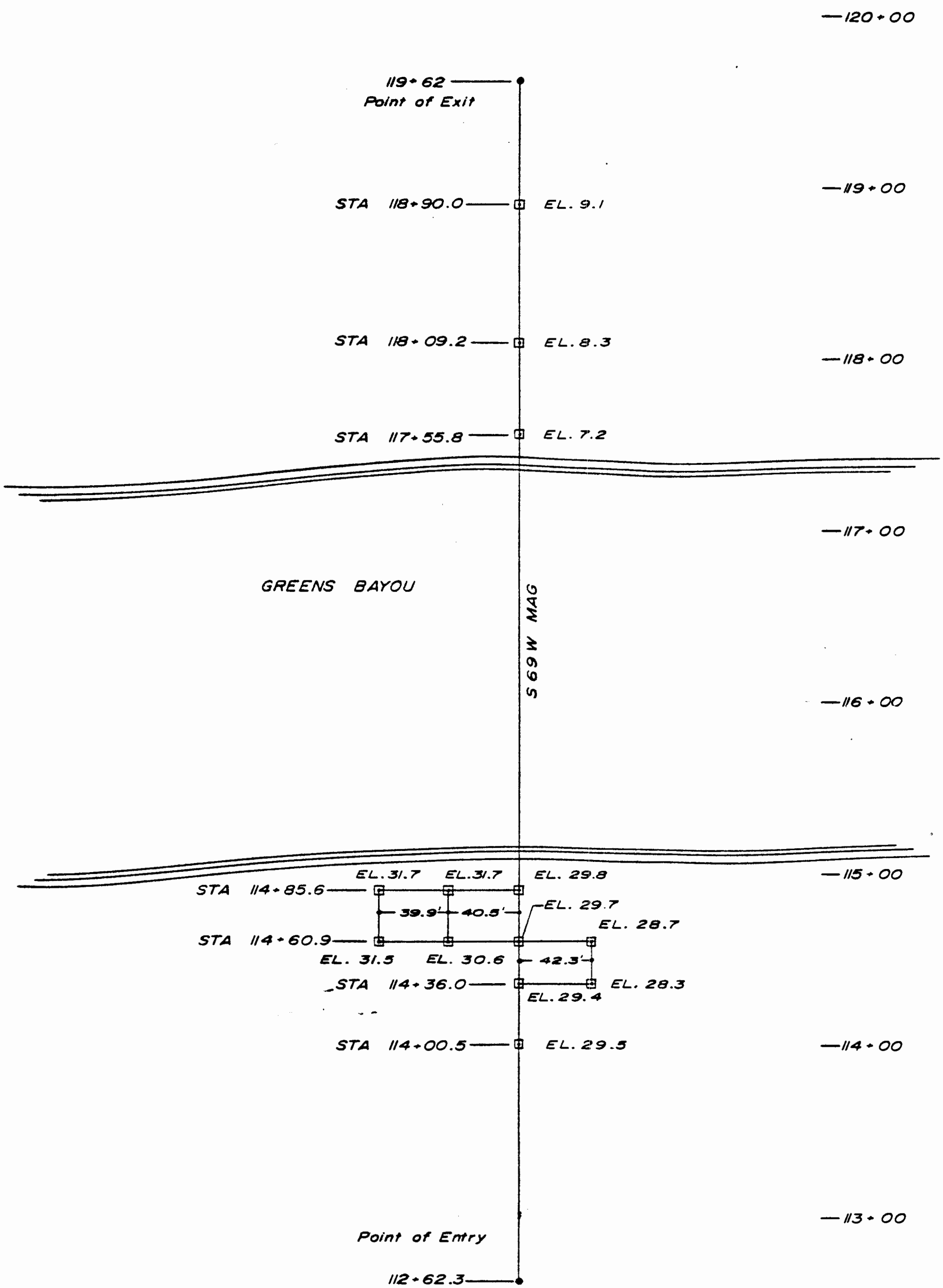
FIGURE 2

Transmitting Antenna Placement

Large Diameter Bore Machine 2-27

TIDRIL CORPORATION

13 Feb. 1978



GREENS BAYOU CROSSING
Magnetometer Stations
TITAN CONTRACTORS CORP.
14 Feb. 1978

FIGURE 3

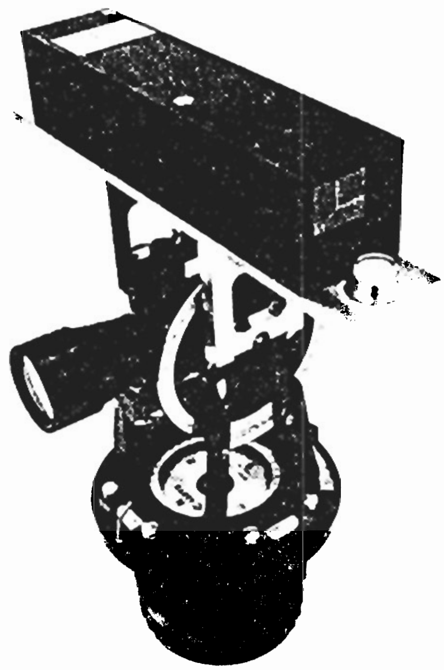


FIGURE 4

MAGNETOMETER/TRANSIT SETUP

A proprietary calculation program was prepared for the TI-59 programmable calculator/printer combination which took data from two receiver positions plus an initial estimate of distance along the desired arc and calculated the following transmitter parameters:

Dipole moment (complex)
Elevation angle
Azimuth angle
Depth from surface (OMST reference)
Range from entry
Distance off track (right or left)

An iterative type program was used because of the lack of precise calibration data, other unknowns, and the simplicity of the TI calculator. As a result the calculation process was very slow and it typically took about 6 hours to get answers accurate within a couple of percent, which was barely consistent with drilling progress. (Simple single point programs were also used to get a quick estimate of position which was useful if the moment was accurately known.) It is estimated that accuracies better than one foot were achieved for measurement ranges up to several hundred feet.

A summary plot of the measurement results is shown in Figure 1 which compares the Develco locator data and the Titan inclination data with respect to the desired path. We were not able to get data or, in some cases, reduce available data at every point due to time limitations. However, the trends are very clear and consistent with actual events and the final result. For example, there was a consistent left track error until the pipe string started to roll to the right. This forced the drill into a right track error which was minimized and eventually recovered by steering to the left as can be seen from the record. The Titan estimate of profile is based on plotting their internal inclination measurement data by a tangential method. The Titan results show a clear cumulation of error in the upward direction which was probably due in part to instrumentation problems. Note that the locator method gives a true measurement of actual position at each transmitter location with an accuracy that only depends on measuring the received fields correctly and that does not accumulate over the path. The fact that, with the advice to steer hard left and up on the final section, the drill came out and knocked over the post marking the desired exit point, as shown in Figure 5, tends to substantiate this point.

In conclusion, this job has shown that the basic locator techniques can be used successfully on at least one kind of drilling navigation problem. The equipment can be easily designed for field use and automated to provide nearly instantaneous data on drill position probably even while drilling. It will be straightforward to adapt the calculation methods that have been developed to a small computer, which will reduce computation time to a few minutes at most. By using a more powerful antenna and a more sensitive receiver, the measurement ranges can be extended considerably. Also by using multiple self-compensating receivers and an appropriate reference source, it is possible to eliminate the need for precisely surveying the receiver locations or to permit use where surveying is not possible, such as under water. In summary, it is clear that the method is practical and has considerable commercial potential.

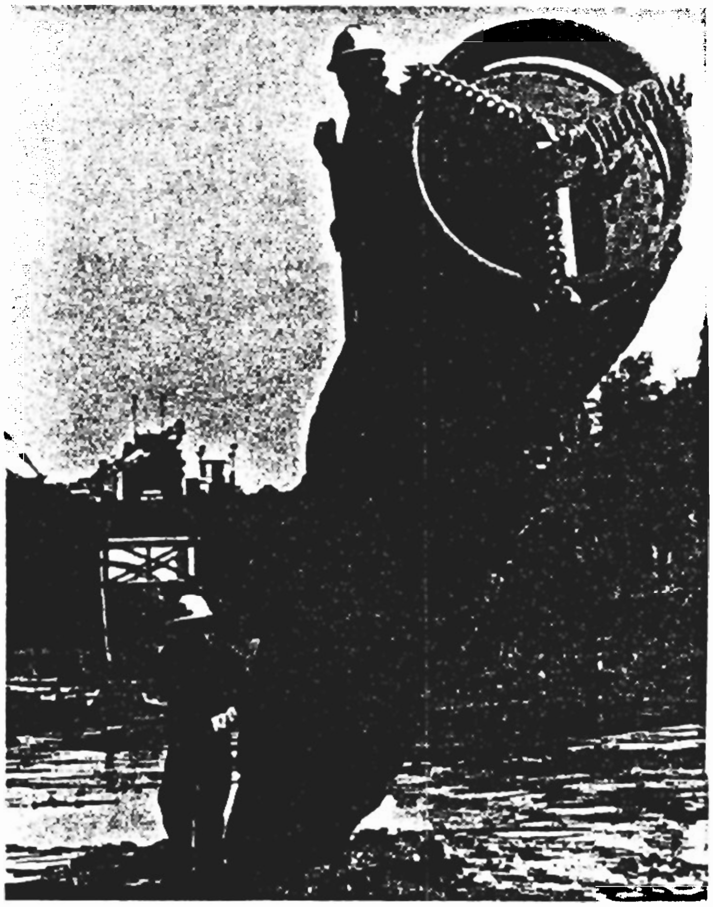


FIGURE 5

DRILL AT EXIT POINT

TITAN REFERENCES

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