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Walk-over Locating Technology

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ABSTRACT
This paper describes the walk-over locating technology used in horizontal directional drilling. It covers both the fundamentals of the technology and practical applications. The paper begins with a comparison of the two types of magnetic fields used for in-ground locating. The cylindrical magnetic field is used for locating wires, pipes, and conduits, while the dipole magnetic field is used to track drill heads. Plots show the magnitude of the signal intensity as detected by various receiver antenna configurations for the two types of fields. The paper then goes on to show the flux patterns on the surface of the ground and their importance to locating. A description is given of the various ways that different dipole tracking receivers can process the magnetic field information to locate the in-ground magnetic field source and determine its depth and orientation. The methods described include the use of magnetic field intensity, flux line orientation, and gradients of the field intensity. The ability to predict the location and depth of the boring tool at a point in front of its current position is discussed, including how this feature can be used to guide the drilling process. Finally, the paper describes a novel device that can represent the tracking transmitter's position on a display much like a radar screen so that the position of the transmitter relative to the receiver can be displayed regardless of the orientation of either device. This device uses both the magnetic flux lines and the intensity of the field for locating the transmitter, and its design appears to be the next major advancement in walk-over locating technology.

Keywords: depth measurement, horizontal directional drilling, magnetic fields, receiver, transmitter, walk-over locating

INTRODUCTION

The concept of using trenchless methods to place utilities in the ground is not new. For some time, impact tools and wet boring have been used for short runs. Controlling a drill's direction and measuring its position with a navigation system was first applied to river crossings using large drill rigs. The guidance systems used on these river-crossing rigs were derived from the oilwell drilling industry and were large and expensive. In the 1970s and 1980s, the increasing necessity for electric cable replacement and reinforcement, along with gas conversion in cities and residential areas, established the need for smaller and less costly ways to install utilities over larger distances.

With the development of smaller-diameter horizontal directional drilling (HDD) equipment, a new smaller and less costly type of guidance system was required. With these objectives in mind, attention was directed to cable-locating technology. Electronic cable-locating systems include a transmitting device that induces a very-low-frequency (VLF) magnetic signal onto the cable. Typically, the frequency used is less than 80 kHz. The locating system also has a receiving device that detects the signal on the cable and provides some indication to the operator of at least the intensity of the signal. The first HDD tracking was done using a cable-locating receiver. The shortcomings of cable-locating equipment used for HDD tracking led to the development of new devices that addressed the differences of the two locating requirements. This paper discusses the evolution of the transmitting and receiving methods and devices currently used with HDD, VLF magnetic tracking equipment, more commonly called "walk-over" tracking systems. It covers the techniques used to locate and measure the depth of a transmitter in a drill head and provides an analysis of the accuracy of the various techniques.

CABLE-LOCATING SYSTEMS

The cable-locating equipment consists of two devices: a transmitter and a receiver. The transmitter induces a signal on the cable, while the receiver is used to detect the signal along the cable. The following sections provide details on the transmitter, the receiver, and the cable-locating process.

Cable-Locating Transmitters

The transmitter used for locating cables is commonly battery powered and consists of an oscillator and an amplifier. The output of the transmitter is connected directly or inductively to the cable and the ground. The connection induces a current in the cable that oscillates at a specific frequency and produces a magnetic field that oscillates at the same frequency.

Some basic assumptions for cable locating are that the cable extends in a relatively straight line and that the locating is not near either end of the cable. Also, the receiving device is assumed to be responsive only to the magnetic field component of the signal emanating from the cable. With these assumptions, the magnetic signal becomes a two-dimensional cylindrical field independent of position along the cable (see Figure 1).

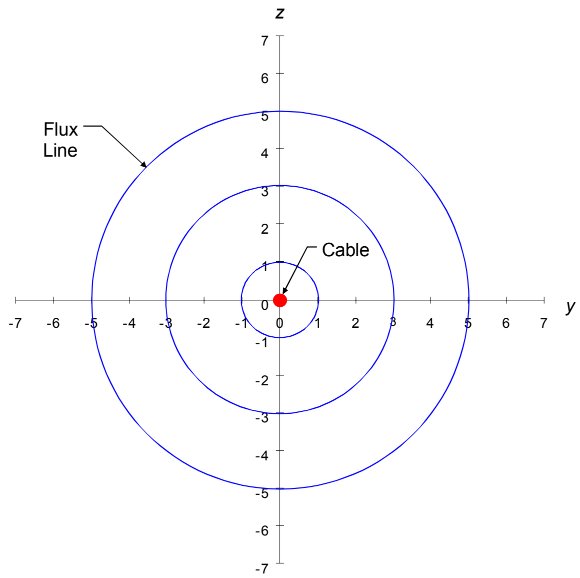

Figure 1. Magnetic Cylindrical Flux Lines Generated by Current Flowing in a Cable

The magnetic field strength of a two-dimensional cylindrical field can be expressed as:

$$B = c/r \tag{1}$$

where c is a proportionality constant dependent on the current flowing in the cable, and r is the radial distance from the cable.[1] The current flows down the cable and returns through the ground. If there is any resistive or capacitive coupling between the cable and the ground, then the current will diminish as a function of the distance from the current-inducing transmitter. Therefore, another assumption has to be made—the change in current along the cable is assumed to be gradual enough that the two-dimensional cylindrical field is essentially preserved locally. Equation (1) shows that it is not possible to determine radial displacement based solely on the magnetic field strength because the proportionality constant, which depends on current that varies along the cable, is unknown.

Cable-Locating Receivers

Assuming that the above restrictions are met and that the magnetic field emanating from the cable is essentially cylindrical, let us now turn our attention to the receiving device used to locate the cable. The simplest device for detecting a magnetic field is a coiled loop of wire with a shield. The shield is a conductive wrapping over the loop that does not fully complete the loop. The purpose of the shield is to prevent the loop from responding to the electric field, which generally contains electrical noise. Aside from excluding this noise source, the electric field should be eliminated because it does not decay in the same manner as the magnetic field. Often, a high-permeability rod made of ferrite material is inserted in the loop to enhance the signal. The loop thus constructed is highly directional and will only measure the intensity of the magnetic flux normal to the loop. The loop and rod are generally referred to as an antenna. The oscillating magnetic flux induces a voltage in the antenna that is amplified and displayed by circuitry in the receiver. A receiver of this design is referred to as a single-axis receiver, because the receiver will only respond to the flux along the axis of the antenna. An example of a single-axis receiver is shown in Figure 2.

Figure 3 shows the transverse (perpendicular to cable) magnetic field strength at ground level (flat surface signified by *x-y* plane) for a cable buried at constant depth. The intensity is represented as displacement along the vertical axis. This figure reveals that the single-axis receiver measuring the transverse field strength with its simple antenna arrangement can provide an accurate means of locating a line on the surface directly above the cable.

[1] See section on "Notations and Units" at the end of the paper.

Figure 2. Single-Axis Receiver (Metrotech® 810 Radio Frequency Line Tracer)

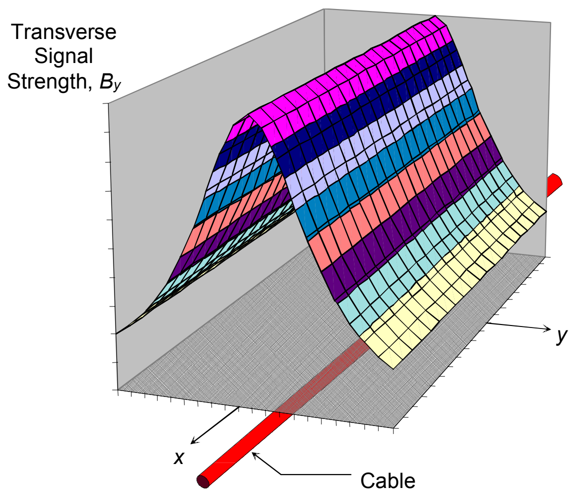

Figure 3. Signal Strength Field Produced by a Buried Cable (Flux Lines Are Aligned Transverse to Cable)

At any time, the direction of the transverse component of the magnetic flux emanating from the cable can be determined by simply rotating the single-axis receiver until a peak is found. Moving the receiver in the direction determined by this manipulation provides the most direct path to the surface location directly above the cable. Even with the single-axis receiver not optimally aligned, the peak found by walking in a straight line will be directly above the cable. It is difficult to go wrong with this system, providing the base assumption of a cylindrical magnetic field is not violated. Of course, the effects of multiple cables in the same area and other sources of interference can make cable locating more of a challenge.

Some cable-locating receivers, like the one shown in Figure 2, not only sense the magnitude of the magnetic field, but also its lateral gradient. By sensing the lateral gradient, it is possible to provide a left-right indication of the cable's position. The vertical gradient of the magnetic field over the cable is used to determine depth, as will be discussed later.

HDD TRACKING SYSTEMS

The basic tracking system for current HDD operation is composed of a transmitter that fits inside the drill head or a special housing and a portable receiver that an operator uses to locate the transmitter and determine its orientation and depth. Orientation data include the left-right direction determined by the magnetic field and roll and pitch measurements taken by sensors in the transmitter. Roll and pitch along with transmitter temperature and battery status are transmitted to the tracking receiver for display. Advanced systems also have auxiliary remote displays to present tracking data at the drill rig to aid in controlling the drill. This paper is restricted to a discussion of the basic principles used to transmit and receive magnetic signals and how the received magnetic signals can be used to track and determine the depth of the transmitter. The specific internal sensors used in the transmitter and the communication schemes used to get the data to the surface will not be covered.

HDD Tracking Transmitters

The difficulty in applying line-locating technology to HDD is that a major requirement of the cable-locating process is violated—the desired location is at the *end* of the drill string rather than in the middle of a long cable. The solution accepted was to apply technology that had been used for tracing sewer lines and tracking unguided drills (see Mercer, 1997, 1998a). This technology employed a dipole magnetic field rather than the cylindrical field used for cables. The dipole field allows for point rather than line location; however, the dipole field is more complex.

Figure 4 shows the flux lines for a magnetic dipole.[2] The field is axisymmetric, and the total signal intensity decays inversely as the cube of the distance along any radial line emanating from the dipole. An antenna, constructed in a similar manner to the single-axis receiver antenna previously described, produces this field when current from an oscillator flows into the coil. The device that produces the dipole field, including an oscillator, power supply, and antenna, is called a tracking transmitter.

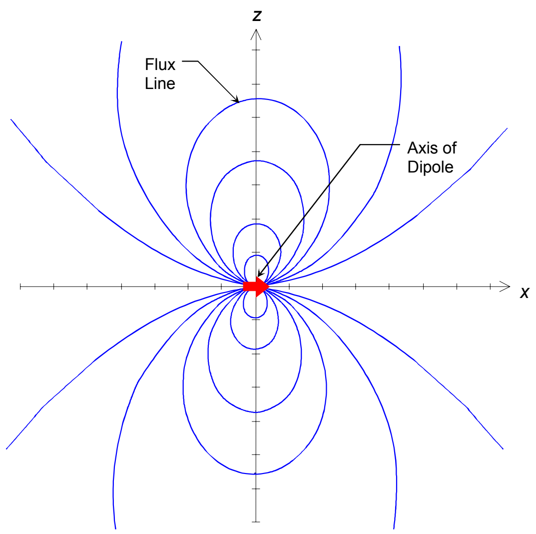

Figure 4. Flux Lines Produced by a Dipole Transmitter

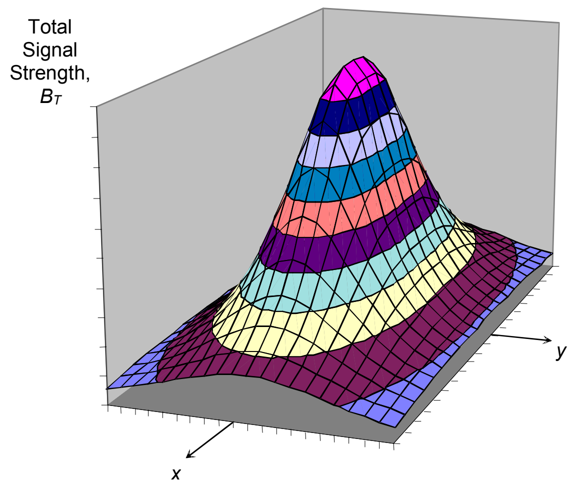

Figure 5. Total Signal Strength Field from a Dipole Transmitter

Figure 5 shows a plot of the magnitude of the magnetic signal from a tracking transmitter[3]. There is a peak over the transmitter with rapid decay in the *y*-direction and less rapid decay in the *x*-direction (along the transmitter's axis). This plot shows that the peak total signal strength alone could be used to locate the transmitter; however, finding that peak is not that easy.

Another and/or supplementary locating method uses the magnetic flux lines. Figure 4 showed the lines as they emanate from the transmitter and return to it. Another plot useful in understanding the behavior of the magnetic field is shown in Figure 6. This plot shows the intersection of the flux lines with the surface for an underground dipole transmitter lying parallel to the surface.[4] The lines appear to emerge from and converge to points ahead of and behind the location of the transmitter. For reference purposes we term these points "front and rear locate points." These points are spaced apart 1.414 times the depth. Another notable feature shown on the plot is the line formed by the locus of points where the flux lines are parallel to the axis of the dipole transmitter. We call this the "locate line." Both the locate line and the locate points provide useful means to locate the underground transmitter.

[2]For a more complete description of magnetic fields see Corson and Lorrain, 1962.
[3]For this plot and subsequent plots, the transmitter is located below the intersection of the *x* and *y* axes and is aligned with the *x*-axis.
[4]For the purpose of simplicity, the discussions in this paper will be limited to level ground and a level transmitter. If the transmitter is not parallel to the surface, appropriate transformations can be made based on the pitch of the transmitter and the tilt of the receiver to compensate.

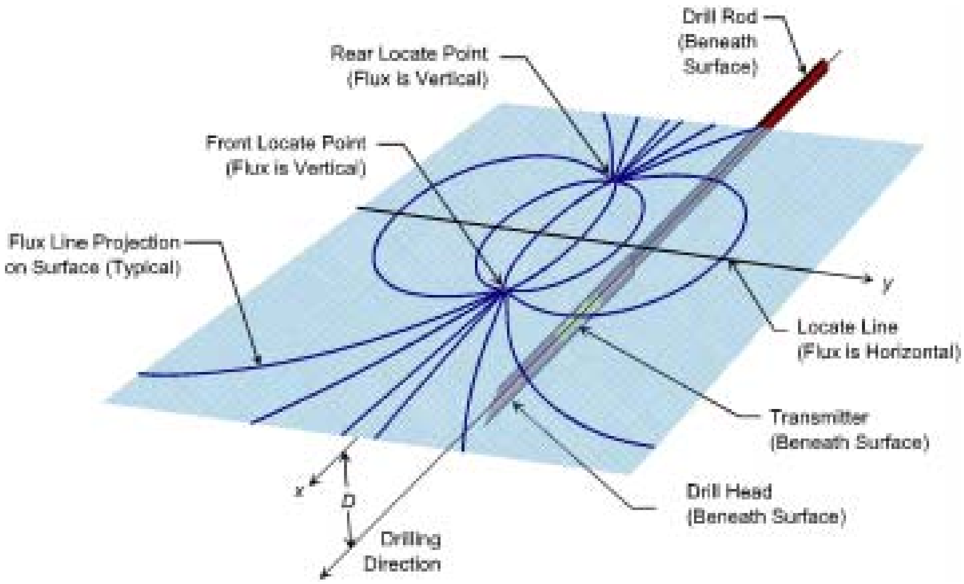

Figure 6. Flux Line Projections on the Surface from a Dipole Transmitter

Figure 6 shows that all the flux lines emerge from and converge to the locate points. By following any of the flux lines, the locator operator will arrive at a locate point. At the locate points, the magnetic flux lines are perpendicular to the surface. The exact distance from a locate point to the position over the transmitter and the transmitter's depth can be calculated from the dipole equations (see Mercer, 1998b, 1999). This makes the locate points useful for controlling the steering of the boring tool. For example, the front locate point provides a prediction of the transmitter's position, which allows the operator to make corrections in anticipation of the boring tool's movement. The line connecting the front and rear locate points also provides an exact heading of the transmitter and shows where the transmitter is located laterally on the locate line.

The locate line, where the flux lines are parallel to the surface, is also useful for locating the transmitter. In particular, the locate line can be used as a Cartesian coordinate in conjunction with the line connecting the two locate points. The intersection of these two lines is the location of the transmitter. Another locating procedure using the locate line is to first find the line, then move along the line until a peak signal is found that corresponds to the transmitter's location. A further use of the locate line is to track the transmitter from a lateral offset line. Because the line is perpendicular to the transmitter, it can be used to establish the transmitter's heading and longitudinal location. This information, in conjunction with the depth and pitch of the transmitter, can assist the drill rig operator in making steering decisions.

HDD Tracking Receivers - Locating

The following sections describe the devices and methods used to measure the magnetic field, gradients in the field, and the flux line orientation to establish the dipole position, orientation, and depth.

Single-Axis Tracking Receivers

We have already discussed the single-axis receivers used to find buried cables. These receivers were also the first to be used for HDD dipole transmitter tracking. As previously discussed, this type of receiver works quite well to find long, straight buried cables where the field shape is cylindrical. However, when this receiver is used to find a dipole transmitter, the locating technique is much more involved.

Figure 7 shows the signal strength field measured by a single-axis tracking receiver when aligned with the axis of the dipole transmitter. There are three peaks in the field: one peak over the transmitter and a pair of lesser peaks ahead of and behind the transmitter. Locating operators call these lesser peaks "ghosts", and it is not uncommon to get these confused with the peak over the transmitter. Figure 7 assumes that the operator knows the direction of the transmitter's axis, but that is not always the case.

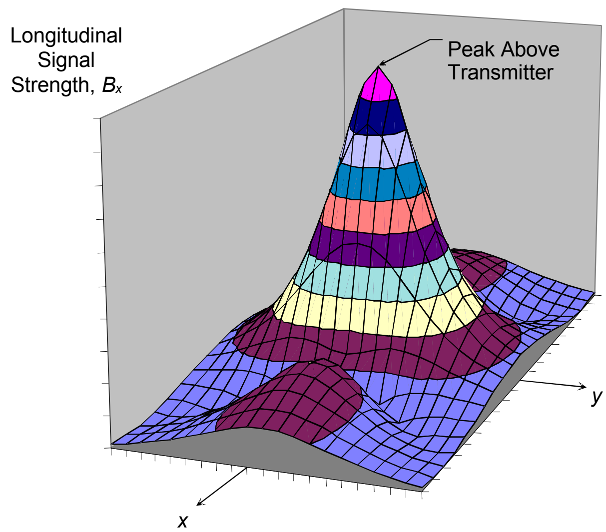

Figure 7. Signal Strength Field Seen by an SA Tracking Receiver Aligned with the Direction of Drilling

Figure 8 shows the signal strength field if the single-axis receiver is aligned transverse to the transmitter's direction. For this situation there are four peaks, none above the transmitter. At other alignments, the field consists of combinations of Figures 7 and 8, making the locating process an art using the single-axis receiver.

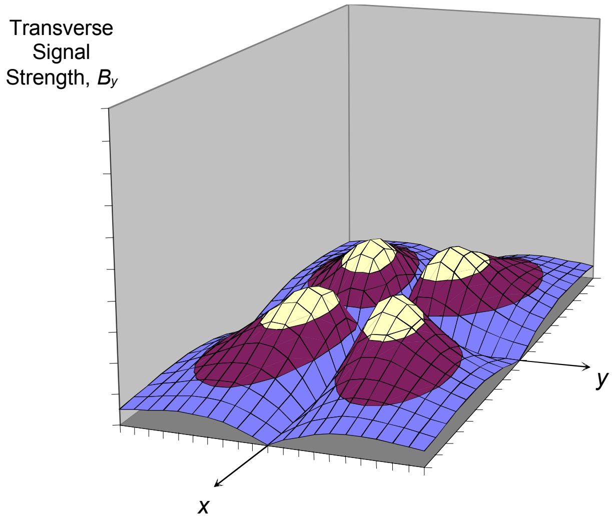

Figure 8. Signal Strength Field Seen by an SA Tracking Receiver Aligned Transverse to the Direction of Drilling

Field Gradient Tracking Receivers
A more sophisticated adaptation of the single-axis receiver is shown in Figure 9. This device, developed by the author and Albert Chau in 1986 for FlowMole (now UTILX), uses five antennas aligned parallel to the longitudinal axis of the transmitter. This type of device is classified as a field gradient tracking receiver. Two of the antennas are positioned fore and aft and are used to obtain a balance or differential null corresponding to the position of peak signal strength. The remaining three antennas are arranged coplanar and provide both vertical and horizontal gradients of the longitudinal magnetic field. Arrows on the display direct the operator fore and aft until the peak signal is found. Then a microprocessor in the locator uses the signal strength from the coplanar antennas to determine both the depth and lateral offset of the tracking transmitter relative to the tracking receiver's position. This receiver offers improvements over the single-axis receiver, but there are still pitfalls in its use. First of all, the operator has to be aligned with the direction of drilling, which is not always known. Also, the operator must remain between the front and rear locate points or else the arrows will misdirect the operator.

Figure 9. Field Gradient Tracking Receiver (FlowMole® FlowCator®)

Magnetic Vector Tracking Receivers
Many of the problems encountered with the single-axis receiver can be reduced or eliminated by adding a second locating antenna, orthogonal to the first. Figure 10 shows this "X" antenna configuration. This combination of antennas provides much more information about the magnetic field than the single-axis receiver can. It not only measures total field strength in the plane of the antennas from the magnetic vector components, but also provides the flux line

orientation. Currently, all HDD locating equipment manufacturers employ elements of this type of receiver in their most advanced designs. When this type of receiver, called a magnetic vector tracking receiver, is aligned with the direction of drilling, the total in-plane magnetic field, measured as a vector sum, has only one peak—and that is over the transmitter. There are still multiple peaks when aligned transverse to the transmitter's direction, but the flux line orientation information provides an additional means to overcome this ambiguity. Using this receiver to measure the orientation of the flux lines provides a much more accurate means to locate the transmitter than using just signal strength. The magnetic vector tracking receiver provides a systematic procedure for locating the transmitter even when the direction of the transmitter is unknown (see Mercer, 1998b, 1999).

Figure 10. Magnetic Vector Tracking Receiver (DigiTrak® Mark III Receiver)

The latest advancement in locating technology eliminates any receiver alignment requirements by using three orthogonal antennas. This three-dimensional vector tracking receiver detects the total local flux orientation and vector flux magnitudes. It displays a locate point or line much like a target on a radar screen. Unlike other receivers that show a simple linear view or two pairs of arrows, the three-dimensional vector tracking receiver gives a complete bird's-eye view of the locating area. Unlike prior designs, the receiver accommodates all heading orientations relative to the transmitter. Figure 11 shows the receiver and its display screen. The locate points are represented as a target on the screen, and the receiver is shown as a box. The operator simply walks as directed on the screen until the target is positioned in the box. Internal tilt sensors correct for the tilt of the receiver, eliminating any requirement for the operator to level the receiver for accurate measurements. With this receiver, the operator only needs to be within range to be directed to a locate point or to the transmitter. The three-dimensional vector tracking receiver computes both the depth over the transmitter and the predicted depth at the front locate point (depth measuring techniques are described in the next section).

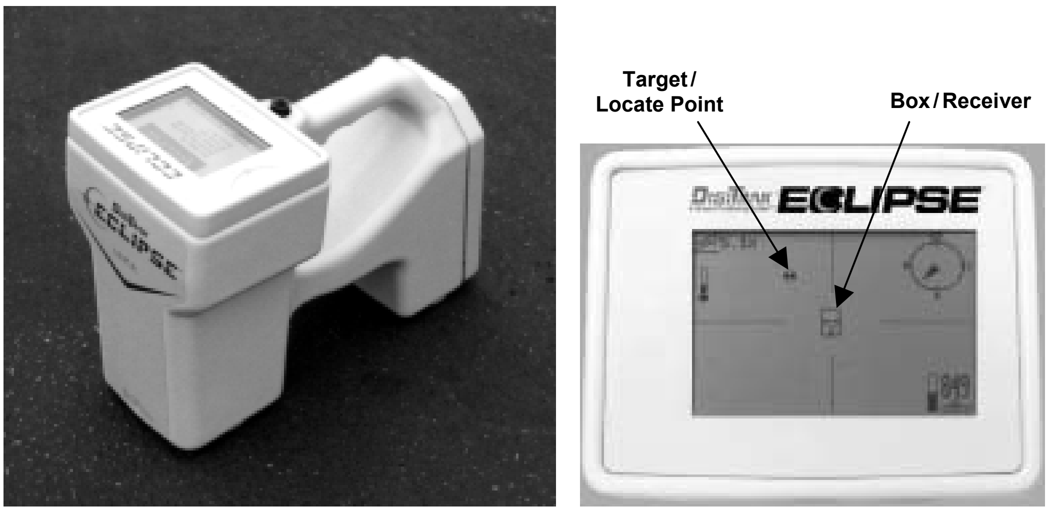

Figure 11. Three-Dimensional Vector Tracking Receiver and Display Screen (DigiTrak® Eclipse™ Receiver)

The positional accuracies of the various receivers and locating algorithms differ. Table 1 provides a comparison of the various locating procedures. The positional accuracy calculations are derived from the dipole equations (see Mercer, 1998b, 1999) and use dimension and detection accuracy values typical of current receivers.

Table 1. Comparison of Locating Accuracies with Different Types of Tracking Receivers

	Type of Receiver		
	Single Axis	**Field Gradient**	**Magnetic Vector**
Locating Accuracy			
Along Path			
Over Transmitter	$\frac{\Delta x}{D} = \pm\sqrt{\frac{2}{9}E_R}$	$\frac{\Delta x}{D} = \pm\frac{1}{9}\frac{D}{d}E_R$	$\frac{\Delta x}{D} = \pm\frac{1}{6}E_R$
Vertical Flux Point	NA*	Note 1	$\frac{\Delta x}{D} = \pm\frac{3}{8}E_R$
Transverse to Path			
Over Transmitter	$\frac{\Delta y}{D} = \pm\sqrt{\frac{2}{3}E_R}$	$\frac{\Delta y}{D} = \pm\frac{1}{3}\frac{D}{d}E_R$	Note 2
Vertical Flux Point	NA	Note 1	$\frac{\Delta y}{D} = \pm\frac{1}{2}E_R$
2% Detection Accuracy at 6 m (19.7 ft)			
Along Path			
Over Transmitter	±40 cm (16 in.)	±13 cm (5 in.)	±2 cm (0.8 in.)
Vertical Flux Point	NA	NA	±5 cm (2.0 in.)
Transverse to Path			
Over Transmitter	±69 cm (27 in.)	±40 cm (16 in.)	Note 2
Vertical Flux Point	NA	NA	±6 cm (2.4 in.)

*NA - Not applicable
Note 1 - Limited by the signal-to-noise detection capability of the receiver.
Note 2 - The magnetic vector receiver can use signal strength like the single-axis receiver to find the lateral locate line over the transmitter with the same resulting accuracy as the single-axis receiver.

HDD Tracking Receivers - Depth Computation

Gradient Method

Depth measurement can be done using two principal means: gradient and calibration techniques. The gradient technique was first described in regard to the cable-locating industry in a 1965 article in the *Bell Laboratories Record* (Young, 1965). Figure 12 shows the Bell Laboratories Depthometer. This device uses two parallel antennas to measure the gradient of the horizontal field in the vertical direction. The relationship used to compute the depth of a dipole transmitter based on the signal strength ratio is

$$D = \frac{d}{\left(\frac{B_1}{B_2}\right) - 1} \tag{2}$$

where D is the distance from the transmitter to the lower antenna (antenna 1); d is the distance between antenna 1 and antenna 2; and B_1 and B_2 are magnetic signal strengths measured by antenna 1 and antenna 2, respectively.

Early receivers used an analog meter to display signal strength in combination with manual controls to adjust the gain. After positioning the locator above the transmitter, the gain was adjusted to position the meter needle on a line marked near the full range of the display. A switch was then depressed that caused the electronics to switch from the bottom antenna to the top antenna at a greater distance from the transmitter and consequently lower signal strength. The meter was marked to display what the corresponding depth would be. New versions of this type of receiver use digital electronics to calculate the depth based on equation (2).

One difficulty with this type of depth calculation is that its accuracy decreases with depth, because it is a function of the ratio of the depth to the vertical separation of the two antennas in the tracking receiver. For depths on the order of a few antenna separations, the accuracy is generally acceptable. But at greater depths, the accuracy rapidly decreases and becomes unacceptable.

Figure 12. 1965 Bell Laboratories Depthometer

Calibration Method
Another means to measure the depth is to work directly with the signal strength and perform a calibration function that relates the depth directly to the measured signal strength. This method requires that the dipole field emitted by the transmitter be constant and uniform. Unlike the buried cable with its varying current, the dipole transmitter can be designed to provide an invariant dipole field. Also, the housing for the transmitter can be designed to emit a constant field independent of the rotation orientation. The dipole field strength varies as the inverse cube of the distance along any ray from the dipole:

$$r = \frac{c}{B^{1/3}} \tag{3}$$

Thus, the system is calibrated prior to drilling by placing the tracking receiver at a known distance from and orientation to the tracking transmitter (installed in the drill head) and measuring the signal strength. The microprocessor in the receiver can then determine the coefficient that relates the distance to the inverse cube-root of the signal strength. This coefficient accounts for the strength of the dipole transmitter, the attenuation of signal caused by the drill head, and the sensitivity of the receiver.[5] One manufacturer has a procedure for calibrating its receiver while the transmitter is in the ground by taking measurements at two points above the surface and calculating the coefficient. The in-ground calibration can accommodate much of the influence caused by highly conductive soils and brackish water.

The calibration method has accuracy superior to the gradient method as the depth increases. The calibration method's accuracy depends only on the signal measuring accuracy of the receiver and does not deteriorate with depth. Table 2 shows the relative accuracy of the two methods and provides computed results[6] for various depths.

[5]The linearity of the receiver is not accounted for in these discussions of depth computation. Another unaccounted for factor is the effect of the medium being drilled, including soil conductivity and disturbances of the magnetic field caused by conductive buried objects. These in-ground factors can adversely influence the receiver's ability to locate and measure depth. Therefore, the operator should always check for consistency of all the data measured by the tracking receiver such as pitch versus depth change and locate point separation (1.414 × depth).
[6]The computed results, assuming 2% measurement error, compare favorably with one manufacturer's published accuracy data.

Table 2. Comparison of Depth Accuracies Using Gradient and Calibration Methods

	Gradient Method	**Calibration Method**
Depth Accuracy	$\frac{\Delta D}{D} = \pm \frac{E_R}{3}\left(\frac{D+d}{D}\right)\left(\frac{D}{d}\right)$	$\frac{\Delta D}{D} = \pm \frac{E_R}{3}$
2% Measurement Error		
at 3 m (10 ft)	±16 cm (6 in.)	±2 cm (0.8 in.)
at 6 m (20 ft)	±58 cm (23 in.)	±4 cm (1.6 in.)
at 12 m (40 ft)	±225 cm (89 in.)	±8 cm (3.1 in.)

CONCLUSIONS

The development of very-low-frequency magnetic locating equipment for use in the HDD industry has rapidly evolved over the last decade. Early tracking receivers used only one component of the signal strength for locating and the field gradient method for measuring depth. Today's tracking receivers use much more information about the field. The latest development uses all three components of the magnetic signal strength and the field vector angles. The displays have evolved from an analog meter, to digital numeric data, to a full graphic display. Locating the transmitter has evolved from an art requiring a great deal of training to a relatively easy-to-learn procedure much less fraught with pitfalls.

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NOTATIONS AND UNITS

B	Magnetic field strength of two-dimensional cylindrical field
B_1	Magnetic signal strength at antenna 1
B_2	Magnetic signal strength at antenna 2
B_T	Total magnetic signal strength
B_x	Longitudinal magnetic signal strength
B_y	Transverse magnetic signal strength
B_z	Vertical magnetic signal strength
c	Proportionality constant relating distance to magnetic signal strength
d	Separation between antennas
D	Depth of transmitter
E_R	Magnetic signal strength measurement error of receiver
r	Radial distance from cable or dipole
x,y,z	Cartesian coordinates
$\Delta x, \Delta y, \Delta z$	Cartesian positional errors