LOCATING SYSTEMS FOR HORIZONTAL DIRECTIONAL DRILLING[*]

John E. Mercer

Digital Control Incorporated, Renton, Washington

Abstract

This paper describes the challenges of locating underground cables and the evolution of cable locating techniques for the task of locating boring tool heads. It compares the signals emanating from cables and horizontal directional drilling tracking transmitters and the various receiving techniques employed. It provides maps of the magnetic signal fields produced by currents induced in cables and by dipole transmitters. It also compares two locating receiver designs and their differing locating algorithms. Finally, it provides theoretical accuracy limits for determining position and depth.

Introduction

Over the last few decades there have been a number of developments in the repair and installation of underground utilities and drainage. Prominent among these developments is the introduction of guided directional drills. Early in guided drilling development there was a clear distinction between the large rigs used for river crossings and the small rigs used for installing utilities in streets. They had vastly different push/pull forces and torques, as well as different guidance systems. Today these distinctions have melded, and the industry has generally adopted the term “horizontal directional drilling” (HDD) for the entire range of applications.

The brain of HDD equipment is the guidance system. Of the guidance systems in use today, walkover tracking devices dominate the low- to mid-range drills. Most of these tracking devices have evolved from cable locating technology and have been adapted to finding the drill

---

[*] Published in two parts in *NO-DIG ENGINEERING*, Vol. 4, No. 4 (1997) and Vol. 5, No. 1 (1998).

head. One technology, however, has been derived specifically for the HDD application. A description of this technology and a comparison with other technologies commonly in use today is provided.

Discussion

Because walkover locating systems generally originated from systems for finding cables in the ground, we shall start the discussion with the assumptions and techniques developed for cable locating. Modern electronic cable locating systems include a transmitting device that induces a signal on to the cable at a very low frequency (VLF). Typically the frequency ranges from 8 to 80 kHz. There are devices that work at frequencies outside this range, but the majority of systems fall within the range. 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 basic assumption for locating a cable is 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 circular field independent of position along the cable (shown in Figure 1).

The magnetic field strength of a two-dimensional circular 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. The current path is down the cable returning through the ground. If there is any resistive or capacitive coupling between the cable and the ground, then the current will not be constant along the cable. Because some degree of capacitive coupling is guaranteed, it is not possible to determine radial displacement based solely on the magnetic field strength because the proportionality constant is unknown. Therefore, another assumption has to be made—the change in current along the cable is assumed to be gradual enough that the two-dimensional circular field is essentially preserved locally.

With the above assumptions for the magnetic field emanating from the cable, 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 (SA) receiver, because the receiver will only respond to the flux along the axis of the antenna.

Figure 2 shows the transverse (normal to cable direction) component of the magnetic field strength at ground level (flat surface) for a cable buried at constant depth. The intensity is represented as displacement along the vertical axis. This figure shows that the SA receiver can provide an accurate means of locating a line on the surface directly above the cable. The locating technique involves simply moving in a straight line until the peak signal is detected. If the antenna is not aligned with the magnetic flux (not transverse to the cable), the only effect is alteration of the intensity of the peak; the shape of the field is preserved. This statement ignores the case in which the antenna is perfectly aligned parallel to the cable where no flux would pass through the antenna. If this case were ever encountered, a slight rotation of the SA receiver about its vertical axis would restore the signal.

At any time the flux direction is determined by simply rotating the SA 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 SA 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 assumptions are not violated. Of course, the effects of multiple cables in the same area and sources of interference can make locating cables more of a challenge.

Once the cable is located, its depth is determined using a ratio technique. Returning to Equation (1) and rewriting for r we obtain:

$$r = c/B \tag{2}$$

In this equation, B is measured with the receiver, but c cannot be determined because we do not know the current. If two measurements are taken along the same radial line perpendicular to the cable, then c can be eliminated as follows:

$$r_1 = c/B_1 \tag{3}$$

$$r_2 = c/B_2 \tag{4}$$

$$r_2/r_1 = B_1/B_2 \tag{5}$$

This means that by taking two measurements the ratio of distances can be determined from the inverse ratio of magnetic signal strengths. The method commonly used to perform this measurement involves the use of a second antenna parallel but vertically separated from the first by a distance d. Substituting $r_1 + d$ for r_2, we can solve Equation (5) for r_1 as:

$$r_1 = d/(B_1/B_2 - 1) \tag{6}$$

Most cable locating SA receivers perform the ratio function by using the same electronics for both antennas and switching between the two antennas. Figure 3 shows a typical arrangement of antennas.

Early SA receivers had a manual gain control and an analog meter. The peak signal was found by continually adjusting the gain to keep the meter needle on scale as the operator moved about the surface. Depth on these receivers was obtained by first establishing a position directly over the cable based on peak signal. Next, the gain was adjusted to set the needle on the meter to a preestablished line on the scale. Finally, the electronic circuitry was switched from the lower search antenna to the upper antenna to measure the signal at the second antenna. Since the upper antenna was farther from the cable, the signal was weaker and the needle would move down the scale. The meter scale was engraved with the corresponding depth. As the technology advanced, automatic gain control and digital depth display were added to the designs. Some units even added additional search antennas to establish whether the cable was to the left or right of the receiver to expedite the locating. The basic functions of these receivers remained unchanged, however, including the limitation of receiving only one component of the magnetic field—they were still SA receivers.

As smaller-diameter HDD equipment was developed, the need arose for a new type of guidance system different from those used on the large river crossing rigs. The guidance systems used on river crossing rigs were derived from oil well drilling technology—the downhole guidance modules were large, expensive, and not readily adaptable to smaller rigs. As an alternative, attention was directed to cable locating technology. The difficulty with this technology was that one basic assumption used in the cable locating process was violated—the desired location was at the *end* of the drill string, rather than along a continuous cable. What was needed was a signal different from the two-dimensional cable signal. Prior locating schemes used for tracing sewer lines and finding blockages, as well as following unguided drills, employed a dipole magnetic field. 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. 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. The field is produced from an antenna constructed similarly to the receiver antenna only without the need for a shield. The equations for the Cartesian vector components of the field are:

$$B_x = m\,(3x^2 - r^2)/r^5 \tag{7}$$

$$B_y = 3\,m\,x\,y/r^5 \tag{8}$$

$$B_z = 3\,m\,x\,z/r^5 \tag{9}$$

and the vector magnitude is:

$$B_T = m\,(3x^2 + r^2)^{1/2}/r^4 \tag{10}$$

where:

$$r^2 = x^2 + y^2 + z^2 \tag{11}$$

Here (x, y, z) is the position where the flux is measured relative to the dipole, the x direction is the orientation of the dipole, and m is the dipole strength.

With the more complex dipole field, locating with an SA receiver is a more complicated procedure. Since the field lines are in planes containing the transmitting antenna (in the direction of the drill string), the receiver is oriented at a right angle relative to its position for cable locating. Also, the signal strength pattern as measured by the SA receiver has regions that can mislead the operator.

Figure 5 shows the signal strength measured by an SA receiver moved over the surface with the receiving axis in the direction of the drill string. The drill in this representation is parallel to the surface. Comparing Figures 2 and 5 provides an understanding of the complexity of locating a boring head relative to a cable. The dipole field has a strong peak in signal strength measured directly over the transmitter, but it also has two other peaks. The two lesser-strength peaks are directly ahead of and behind the transmitter. These peaks can present a problem to a locator operator in that the operator can only determine the field in the immediate vicinity and cannot see the entire field. To establish if the measured peak is over the transmitter, the operator must find another peak and determine whether it is much weaker. This process of finding a second peak takes time, and if the operator continually tracks the drilling progress it is not required. It is not uncommon for the operator to lose track of the peak over the transmitter and mislocate on one of the lesser peaks. This not only causes an error in position but also in depth. The depth is calculated in the same manner as for cables, using a second antenna, except that the depth relationship is now inverse cubic. If the receiver is not over the transmitter, the calculated depth will be erroneous. Operators have traditionally referred to these lesser peaks as ghosts and have been haunted by them.

In the above discussion we have assumed that the operator knows the direction of the drill and has aligned the SA receiver with the drill string. If the drilling direction is not known, the locating becomes significantly more difficult. Figure 6 shows the field strength pattern as seen by an SA receiver held transverse to the drilling direction. This pattern shows four equal peaks—none is located over the transmitter. Unlike the circular field produced by a cable, which appears to change amplitude only with misalignment of the SA receiver, the dipole field appearance changes entirely. In general, the dipole field seen by the SA receiver will consist of a mix of the fields shown in Figures 5 and 6, having as many as seven peaks.

In an effort to find a systematic procedure to locate the drill head, one might try to find the local maximum signal strength by rotating the SA receiver to align the antenna with the horizontal component of local flux lines. Figure 7 is a map of the signal strength obtained using this procedure. This map has a single peak, two nulls, and a string of ridge lines. This would be a very difficult field to interpret, because the operator only knows the local signal strength and its proximate variation.

The SA receiver that was so easy to use with the cylindrical magnetic field emanating from a cable becomes a real challenge to use with the dipole field. The ghosts and orientation sensitivity that did not exist with cable locating become pitfalls with dipole transmitter locating. A major cause of the problem is associated with the receiving antenna. Because the single antenna can only measure the horizontal component of the magnetic field, it cannot respond to locations where the field is vertical. This fact manifests itself as nulls in the receiver response. The total field does not have a null. The nulls are artificially introduced by the SA receiver. The received nulls in turn create the ghosts and ridge lines observed in Figures 5, 6, and 7. Current designs for SA receivers have attempted to compensate for the limitation of searching with only one antenna. Some incorporate another antenna to provide independent information to assess whether the peak is a ghost or the maximum peak. These efforts have aided operators, but are only a patch to the basic problem of searching for only one component of the signal strength.

In an attempt to minimize or eliminate nulls and untoward receiver responses, consider the antenna configuration shown in Figure 8. A pair of antennas is located in the upper portion of the device. These antennas are arranged perpendicular to each other and at a 45-deg angle to horizontal. The electronics in this device are designed to add the signals received by the two antennas as a vector sum. This means that the receiver responds to the total magnetic field contained in the plane of the antennas as opposed to just the horizontal component, as for the SA receiver. This alternate receiver design will be referred to as a vector sum (VS) receiver.

Figure 9 shows the signal map obtained by the VS receiver when the receiver is held in the direction of drilling. Comparing Figure 9 with Figure 5 reveals that there are no ghost peaks. Furthermore, the signal increases monotonically along the direction of the drill to a peak and then decays monotonically away from the peak. This is a much simpler field to locate using just the signal strength.

The above discussion has assumed that the operator knows the direction of drilling. If this is not the case, then we must consider the signal strength map for a VS receiver not aligned with the drilling direction. Figure 10 shows the signal strength map when the VS receiver is oriented transverse to the drilling direction. The map shows two peaks with a null line running between them. The two peaks are along the drill axis as compared to the four off-axis peaks for the SA receiver shown in Figure 6. Although this is an improvement, this is still not a desirable map. At other orientations there will be three peaks produced by the VS receiver as compared to the seven peaks from the SA receiver. Although the three peaks all lie along the drill path, it is not an ideal locating situation.

Following the same procedure for finding a maximum signal at any location as described above for the SA receiver, the VS receiver measures the total magnetic field. This signal strength map, shown in Figure 11, has only one peak. Locating with this technique is unambiguous. A difficulty with this process is that finding the maximum at every point can be time-consuming.

As an alternate method of locating, consider the map shown in Figure 12. This map represents locations where the magnetic field from the dipole is either vertical (two points—one fore and one aft) or horizontal (line in the middle). The VS receiving configuration shown in Figure 8 can detect these vertical and horizontal field locations as signal balance points in the two antennas. Furthermore, by examining the vector rotation of the signal as the receiver is moved forward, the receiver can establish whether the balance is caused by a horizontal or vertical field. This determination is accomplished by designating which antenna has the stronger signal. A simple means to accomplish this is to use "+" and "-" signs associated with the vector sum signal strength. Referring back to Figure 8, the antenna with its axis extending from the lower left to the upper right is designated the "+" antenna. The other antenna is the "-" antenna. Moving the receiver from a location far from the transmitter along a line over the drill path, the signal would be weak and predominately induced in the "+" antenna. Moving closer to the transmitter, the vector sum signal strength would monotonically increase and the vector field would rotate towards vertical. At vertical there would be a balance. With slight movement forward the "-" antenna would have the stronger signal. This "+" to "-" sign flip would be over the point where the field is vertical. Moving forward the next balance point would be over the dipole transmitter. This would be a "-" to "+" flip and the field would be horizontal. Moving on would produce another "+" to "-" flip at the next vertical flux point. A "+" to "-" flip represents a vertical flux pattern and a "-" to "+" flip represents a horizontal flux pattern.

The "-" to "+" flip (horizontal field line) will always occur along the line shown in Figure 12, regardless of the orientation of the VS receiver relative to the axis of the dipole. The "+" to "-" flip can occur at other locations than just the two vertical field locations. One property of this flip is that when the receiver is moved across the vertical field point with a forward motion, the flip will always be “+” to “-”. This relation holds regardless of the azimuth of the approach. Therefore a positive determination of the vertical point is established by approaching the flip point from at least two different directions preferably at right angles to each other.

The vertical flux point ahead of the transmitter is a convenient way to track the drill head. The distance between the two vertical flux points can be shown from Equation (7) to be $\sqrt{2}$ times the depth. This distance-to-depth relationship can be used as a check on the depth determined by the signal strength (details of the depth determination procedure for the VS receiver are described below). The forward point provides some lead in anticipating where the drill is headed. This can be useful when approaching buried utilities in the path of the drill. The combination of the forward and aft points provides an extremely accurate means to aim the drill. Since the transmitter is always located behind the most forward point of the drill, there is no reason for tracking the position of the transmitter rather than tracking the position of the forward vertical flux point. For a typical small-diameter drill head operating at a depth of 4 ft (1.2 m), the forward vertical flux point is about as far in front of the drill bit as the transmitting antenna is behind.

A procedure that provides a simple means to locate the vertical flux points is to move in a straight line with the signal showing a “+”. When the “+” flips to a “-”, make a 90-deg turn. If the signal shows a “-”, turn around and it will show a “+” , then walk forward and repeat the process. This procedure ensures that the movement is toward the vertical flux location. At the second turn, a turning pattern in either the right or the left direction is established; thereafter, turns in the same direction will be repeated at each transition.

Figure 13 shows a set of locating scenarios using the VS receiver based on calculations using the magnetic field equations. The plot is a top view of the tracks taken using the above described locating procedure. The location on the plot x=0, y=1 represents a displacement off to the side of the transmitter equal to the depth. The dipole transmitter is located at x=0, y=0, z=-1. Starting at x=0, y=1, the operator moves along path 1 parallel to the drill path. At x=1, y=1 there will be a flip. The operator determines at this point that a net right turn is required to display a "+". Moving on at x=1, y=0 there will be another flip and right turns will be established. Moving on to the next flip at x=0.707, y=0, the operator will find that any movement from this point will place a "-" on the display, which is an indication that this is the vertical flux point.

For the second scenario, we again start at the same point (0,1), and the operator assumes that the drill is moving off at a 45-deg angle (path 2). The operator moves in the 45-deg direction until reaching the first flip. The movement is continued with three more right turns, which places the operator substantially over the vertical flux point.

For the third scenario, we again start at point (0,1), and the operator assumes that the drill path is almost at a right angle to its actual path. This time the operator's path (path 3) crosses over the line of the drill before reaching the first flip point. With a total of three left turns the operator is placed over the vertical flux point.

As the final scenario (path 4), the operator starts to the left of the path and well in front of the dipole transmitter (2,1). If the operator initially faces forward and to the left, the display will show a "-" which means turn around. From this point the path leads back toward the drill. With a total of two turns the operator is over the vertical flux point.

These examples show that with two to four turns the operator can find the forward vertical point with no sense of the direction of the drill. The same procedure can be used for the aft vertical flux point if a precise heading is desired. This method of finding the vertical flux points provides a systematic procedure that is not available with the SA receiver.

Without the two vertically spaced antennas, the depth cannot be determined in the same manner as with the SA receiver. Instead, the VS receiver uses a calibration procedure. Because the dipole transmitter can be designed to provide constant signal strength and the drill head can be designed to allow a uniform signal pattern around its axis of rotation, there is a useful distinction between the dipole signal and the cylindrical signal. While two signal strength measurements and a ratio are needed to determine the depth of a cable, there is no such requirement for the dipole depth. The dipole depth can be computed directly from the measured signal strength once the proportionality constant is determined. Equation (10) expressed over the transmitter becomes:

$$B_T = m/r^3 \tag{12}$$

The proportionality constant, m, can be determined by measuring the signal strength at a known distance, r, or by taking two measurements at radially separated points. The single measurement method is convenient before drilling starts, and the dual measurement method can be employed when the drill is in the ground and the depth is unknown. This latter scenario could occur if a new VS receiver is required because the one previously calibrated failed or was damaged. In a practical implementation of the dual method procedure, an ultrasonic measuring device measures the distance to the surface of the ground or water at the same instant it takes each magnetic measurement. The difference between the two ultrasonic readings is used for the separation distance in the proportionality constant calculation.

The proportionality constant for the single-point calibration can be determined by taking the cube root of Equation (12) and rearranging terms:

$$m^{1/3} = B_T^{\ 1/3}\, r \tag{13}$$

For the dual measurement calibration, Equation (12) can be used for the two measurements where the separation is d as follows:

$$m^{1/3} = d/(B_{T1}^{\ 1/3} - B_{T2}^{\ 1/3}) \tag{14}$$

Having described both the single-axis receiver and the vector sum receiver and their respective locating techniques, our attention is now turned to the relative accuracy of the two receivers. This analysis is based on equations for the signal strength fields seen by the respective receivers. The calculations represent the theoretical limits and do not include the effects of external factors, which could reduce the accuracy.

For the first analysis we will compare the locating sensitivities. The SA receiver uses only the x-component of the magnetic field for locating, so we can determine its locating precision by performing a Taylor series expansion based on the two locating variables, x and y. Expanding Equation (7) for variations directly above the dipole (x=0, y=0) and nondimensionalizing on the depth yields:

$$B_x/B_{x0} = 1 - 9/2\,(x/D)^2 - 3/2\,(y/D)^2 + \ \ldots \tag{15}$$

where B_{x0} is the magnitude of the magnetic flux directly above the transmitter and D is the depth of the transmitter.

You will notice from this expansion that there are no first-order terms. This fact means that the peak detection scheme used for locating with an SA receiver is inherently not optimal. It needs a rather large displacement to create a measurable signal change.

Now let us examine the VS receiver for locating sensitivity. The along-the-path (x) locate can be performed at three locations: over the transmitter and at the two vertical flux line points. All three locations are found by comparing the signals in the two antennas. An imbalance in the two signals exists because the flux line does not precisely bisect the angle formed by the two antennas. For the case of locating over the transmitter, the imbalance is produced because the flux line is not perfectly horizontal. For the case of locating at the vertical flux points, the imbalance is caused by any x or y deviation of the flux line from vertical.

Over the transmitter, the z-component of the flux causes the imbalance. Making a small angle approximation and using the ratio of the magnetic flux components [Equations (7) and (9)], the antenna imbalance for the two antennas oriented at 45 deg to horizontal can be expressed as:

$$I_{xt} = 6\,(x/D) \tag{16}$$

where I_{xt} is the imbalance normalized on the antenna signal over the transmitter. Notice that there is a strong first-order dependence on the nondimensional displacement, x/D, as opposed to the second-order dependence for the SA receiver.

At the vertical flux points, the along-the-path locate sensitivity is still first order and can be derived using the ratio of x to z components of the flux as:

$$I_{xvf} = 8/3\ [(x - x_{vf})/D] \tag{17}$$

where $(x - x_{vf})$ is the displacement along the x-axis from the vertical flux point.

The transverse sensitivity can be derived using the ratio of the y to z components of the flux as:

$$I_{yvf} = 2\ (y/D) \tag{18}$$

Having described the mathematical analysis for determining the precision for locating with the two receiver designs, we now will provide numerical examples of the expected error. For these comparisons we will use a depth of 20 ft (6 m). Since the parameters have all been nondimensionalized on depth, the errors will scale proportionally for other depths. Also in this comparison we will assume that the detection limit is 2%; that is, the SA receiver can detect a 2% reduction in signal strength over the transmitter. Accordingly, the VS receiver can detect a 2% imbalance in the two perpendicular antenna signals. With these assumptions, the SA receiver has a locate precision of ±1.33 ft (41 cm) along the path and ±2.31 ft (70 cm) transverse to the path. Making the same assumptions for the VS receiver, there are two results for along the path. One result is for finding the locate line over the transmitter (see Figure 12), which is ±0.07 ft (2 cm). The other result is for locating at the vertical flux point, which is ±0.15 ft (5 cm). Transverse path locating at the vertical flux point with the VS receiver has a precision of ±0.20 ft (6 cm).

These comparisons show that there is an order-of-magnitude improvement in using the VS receiver over the SA receiver for locating. At 20 ft (6 m) with a 2% imbalance or signal reduction, the VS receiver is at least 8 to 11 times more precise.

Now let us compare the depth error associated with each of the two previously described depth measurement techniques. For the SA receiver, we take the dipole equivalent of Equation (6) and get:

$$r = d/[(B_1/B_2)^{1/3} - 1] \tag{19}$$

Differentiating Equation (19) with respect to the signal strength ratio, B_1/B_2, and normalizing the result on the depth produces the following expression for the SA receiver fractional depth error:

$$E_{SA} = 1/3\ [(D + d)/\mathrm{D}]\ (D/d)\ E_R \tag{20}$$

Here E_{SA} is the fractional error in determining depth, E_R represents the fractional error in determining the signal strength ratio at the two antennas, D is the depth, and d is the distance between the two antennas. When the depth is large compared to the antenna separation, Equation (20) reduces to:

$$E_{SA} \sim 1/3\ (D/d)\ E_R \tag{21}$$

One can see that with depth the absolute error [that is, the product of Equation (21) with the depth D] will actually vary as the depth squared. Whatever the error is at 10 ft (3 m) it will be 4 times as great at 20 ft (6 m) and 16 times as great at 40 ft (12 m), etc.

The fractional error associated with the VS receiver can be found by solving Equation (13) for r, differentiating with respect to the signal strength, and normalizing on the depth. The result is:

$$E_{VS} = 1/3\ E_B \tag{22}$$

where E_{VS} is the fractional error as above and E_B is the fractional error in measuring signal strength. This expression shows that the fractional error of the VS receiver is constant with the depth; it is not multiplied by the depth. The absolute error then grows linearly with depth so that at 40 ft (12 m) the error will be 4 times as great as at 10 ft (3 m) not 16 times as great, as for the

SA receiver. Therefore, the deeper the drill is going, the more advantage there is to this type of depth determination.

Substituting values into the expression for depth using the SA receiver and assuming a typical antenna separation of 1.5 ft (46 cm), the method shows that a 2% error in measuring the signal strength ratio at 20 ft (6 m) produces a 9.6% error in depth, which is ±1.91 ft (58 cm). For a 2% error in measuring the signal strength in the VS receiver at 20 ft (6 m), the depth error drops to 0.7% or about ±0.13 ft (4 cm).

Table 1 summarizes the results described above and is provided for reference.

Conclusions

This paper showed the added complexity of locating boring tools over locating cables. It has described two different locating devices. One of the devices, the SA receiver, has evolved from cable locating and predominately uses locating techniques and depth calculation methods developed for cables. The other device, the VS receiver, uses procedures developed specifically for locating a dipole transmitter in a boring tool head. The locating accuracy and depth calculation accuracy clearly show the advantage of the device tailored to locating dipoles. The location accuracy for the example provided showed at least an 8 times increase in precision for position determination and a 15 times increase in precision for depth determination.

Table 1. Comparison of Locating and Depth Accuracies with SA and VS Receivers

	LOCATE PRECISION	
	Single-Axis Receiver	**Vector Sum Receiver**
LOCATING ACCURACY		
Along Path		
Over Transmitter	±9/2 $(x/D)^2$	±6 (x/D)
Vertical Flux Point	NA*	±8/3 $[(x-x_{vf})/D]$
Transverse to Path		
Over Transmitter	±3/2 $(y/D)^2$	NA
Vertical Flux Point	NA	±2 (y/D)
2% Detection Accuracy		
at 20 ft (6 m)		
Along Path	±1.33 ft (41 cm)	±0.07 ft (2 cm)
Over Transmitter	NA	±0.15 ft (5 cm)
Vertical Flux Point		
Transverse to Path	±2.31 ft (70 cm)	NA
Over Transmitter	NA	±0.20 (6 cm)
Vertical Flux Point		
DEPTH ACCURACY	$\pm\frac{E_R}{3}\left(\frac{D+d}{D}\right)\left(\frac{D}{d}\right)$	$\pm\frac{E_B}{3}$
2% Measurement Error		
at 10 ft (3 m)	±0.51 ft (16 cm)	±0.07 ft (2 cm)
at 20 ft (6 m)	±1.91 ft (58 cm)	±0.13 ft (4 cm)
at 40 ft (12 m)	±7.38 ft (225 cm)	±0.27 ft (8 cm)

*NA - Not applicable

LIST OF FIGURE CAPTIONS

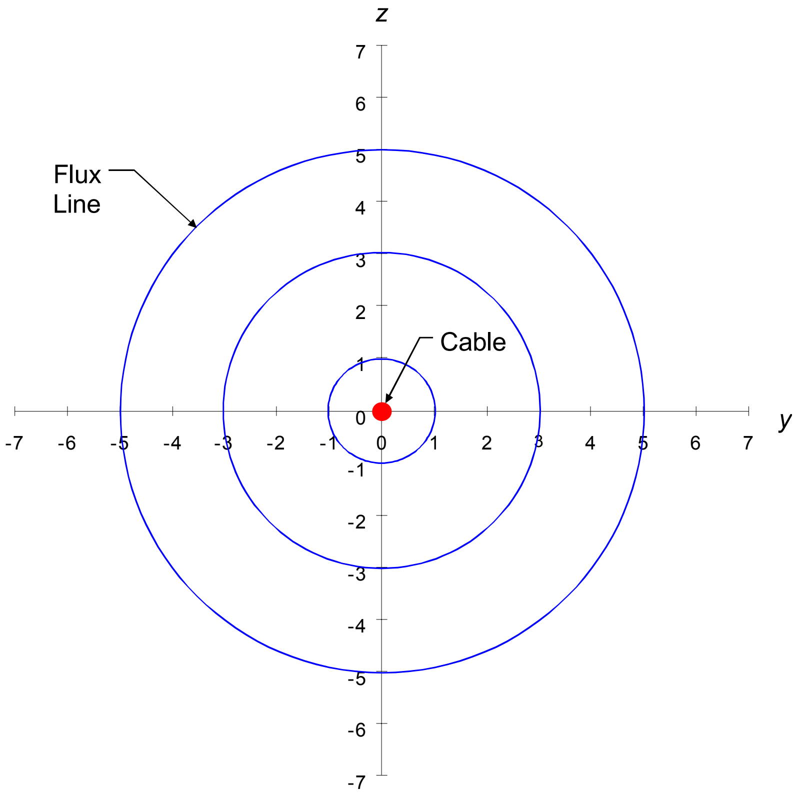

Figure 1. Magnetic Circular Flux Lines Generated by Current Flowing in a Cable

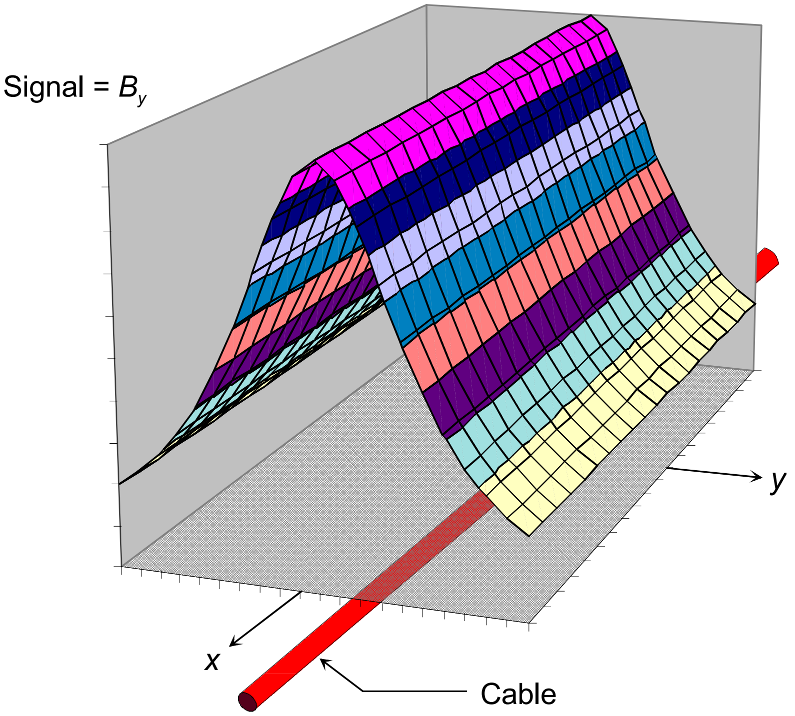

Figure 2. Signal Strength Field Seen by an SA Receiver Aligned Transverse to Cable

Figure 3. SA Receiver

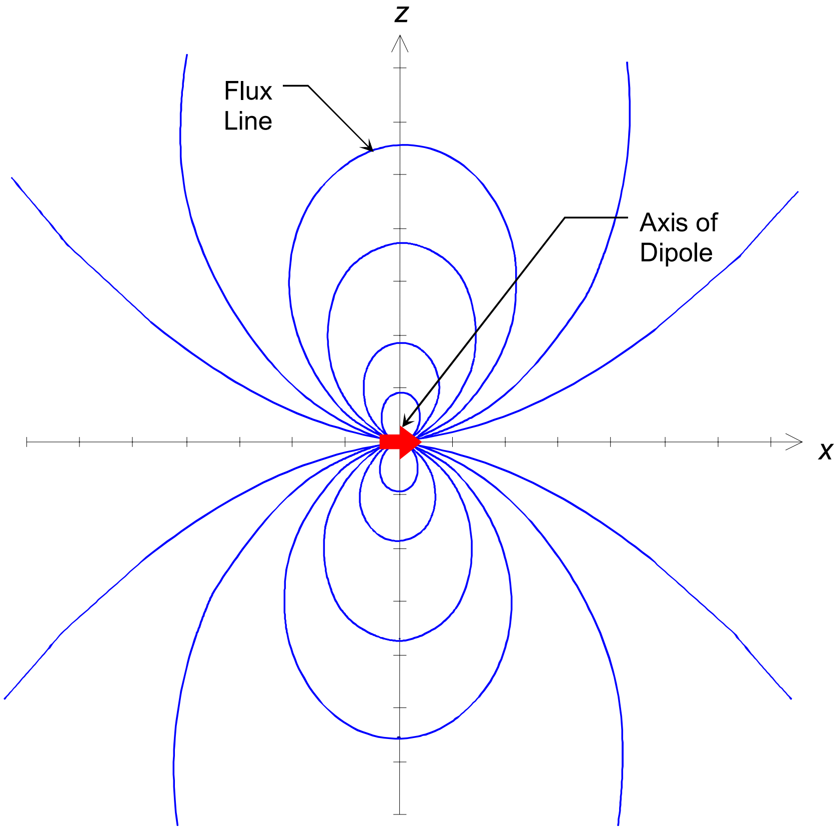

Figure 4. Flux Lines Produced by a Dipole Transmitter

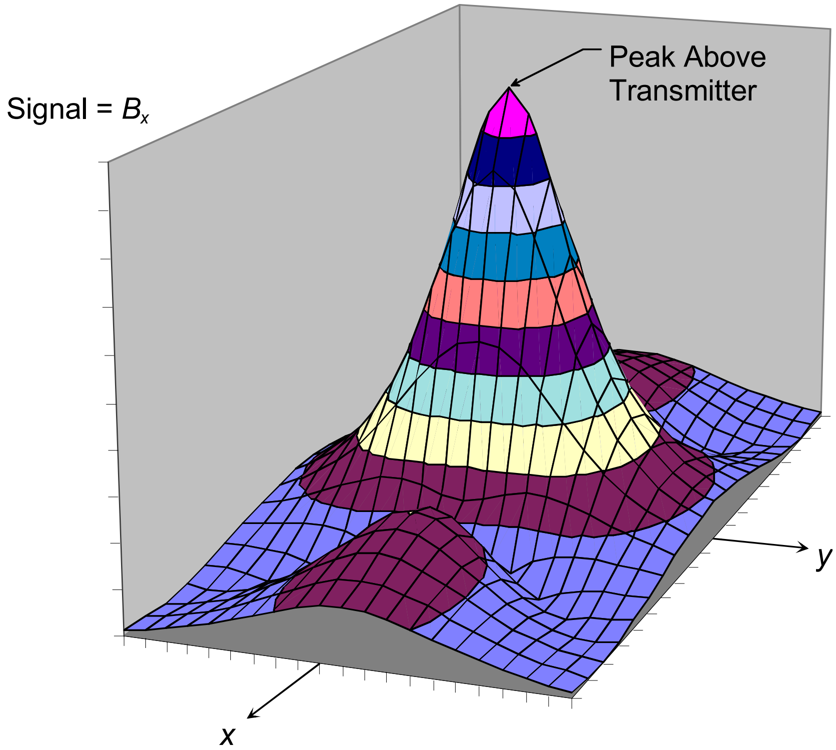

Figure 5. Signal Strength Field Seen by an SA Receiver Aligned with the Direction of Drilling

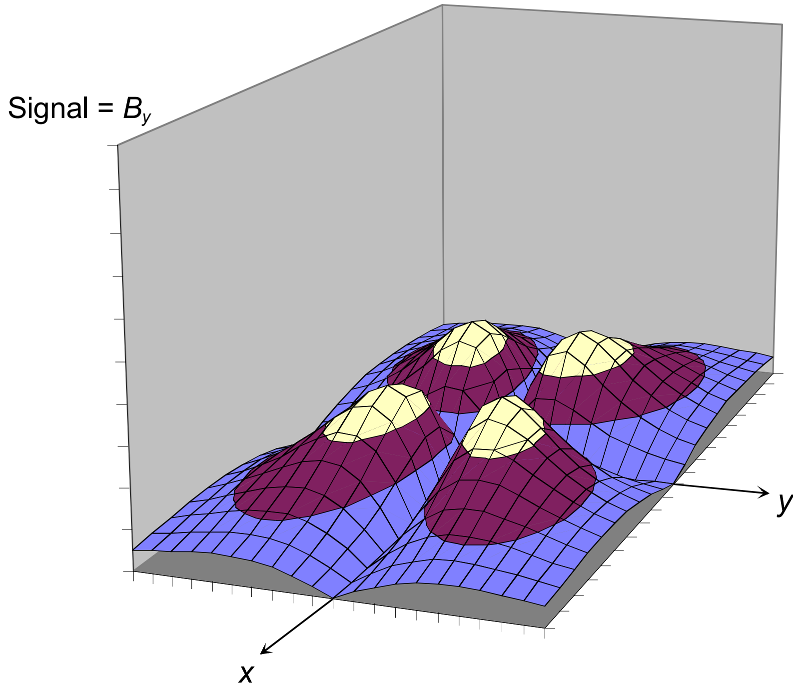

Figure 6. Signal Strength Field Seen by an SA Receiver Aligned Transverse to the Direction of Drilling

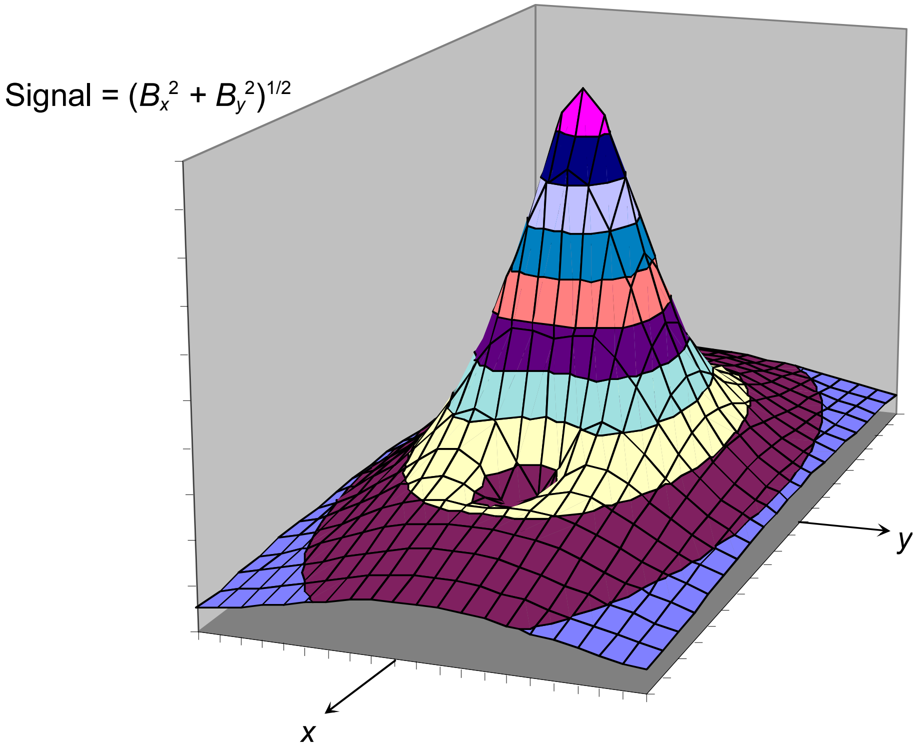

Figure 7. Signal Strength Field Seen by an SA Receiver Algined with the Maximum Signal Strength

Figure 8. VS Receiver

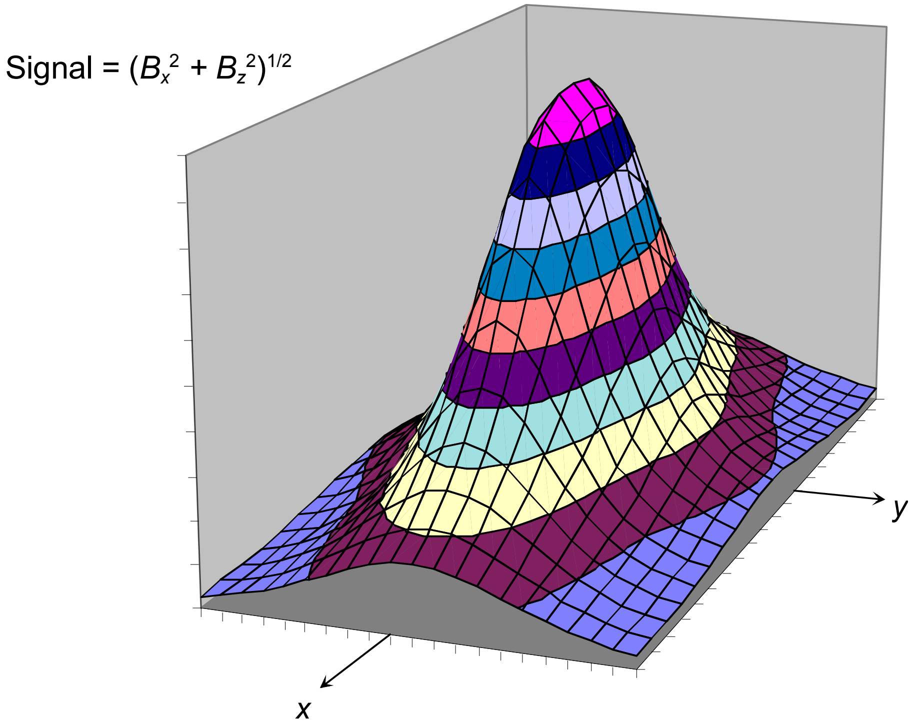

Figure 9. Signal Strength Field Seen by a VS Receiver Aligned with the Direction of Drilling

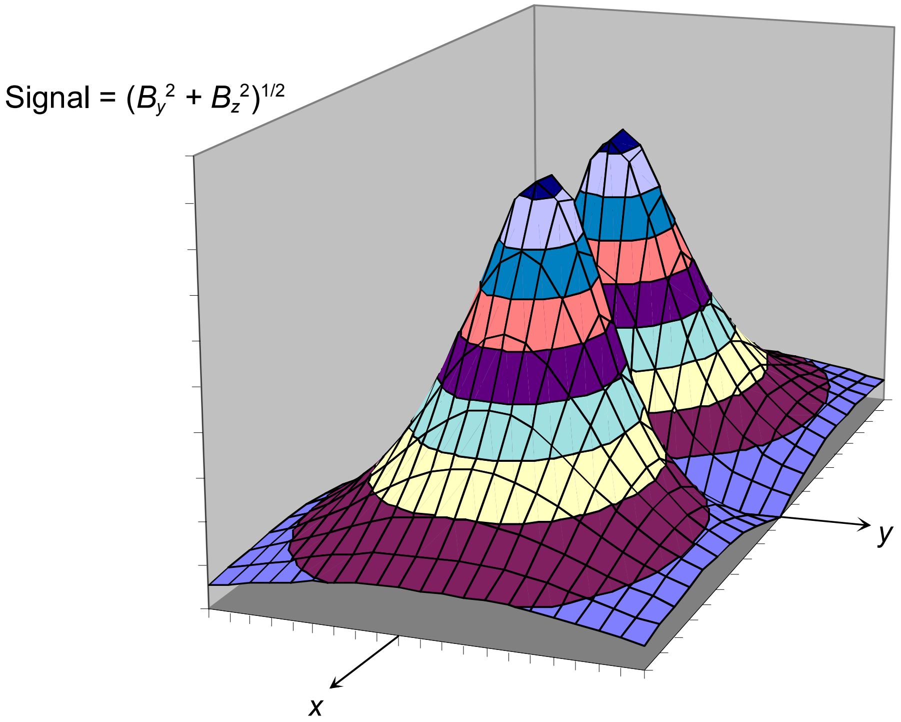

Figure 10. Signal Strength Field Seen by a VS Receiver Aligned Transverse to the Direction of Drilling

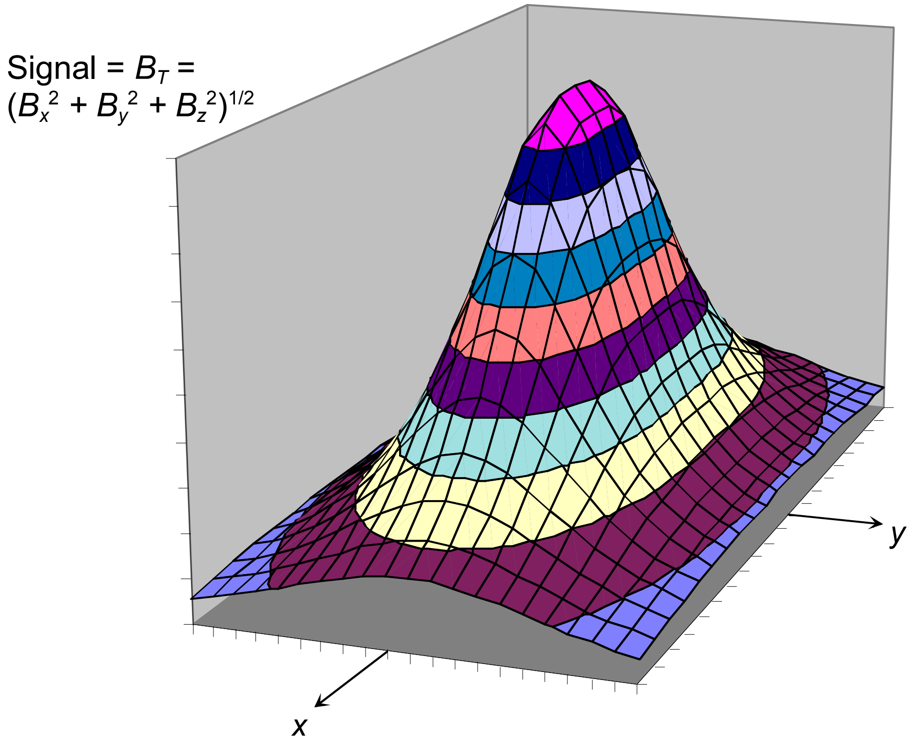

Figure 11. Signal Strength Field Seen by a VS Receiver Aligned with the Maximum Signal Strength

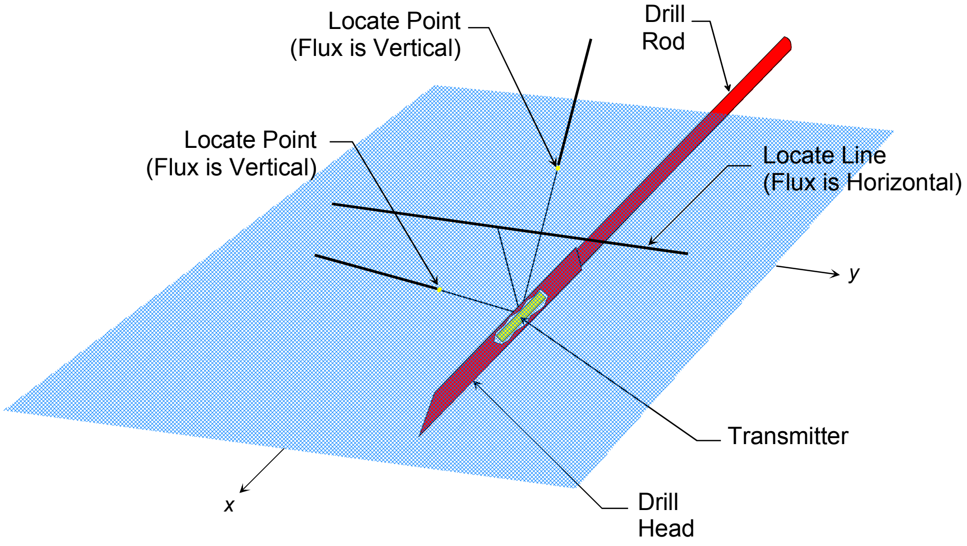

Figure 12. Signal Balance Points for a VS Receiver

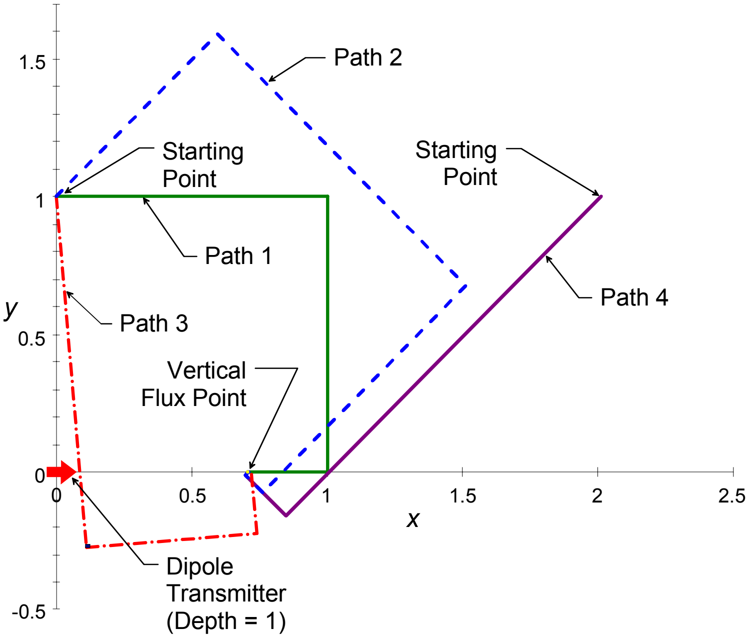

Figure 13. Locating Tracks Using Signal Balance (Top View)