CHAPTER 11

Ahead-of-the-Bit Tools and Far Detection Electromagnetic Tools

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11.1 INTRODUCTION

As described in Chapter 10, The Application of Image Theory in Geosteering, logging-while-drilling (LWD) technology has been used as a geosteering aid in directional drilling. Based on real-time measurements provided by LWD tools, operators are able to make better-informed drilling decisions to improve drilling efficiency as well as to reduce safety risks. The drilling engineers would like to “see” as far as possible the formation boundaries around the drilling bit. To implement the far detections, one of the useful methods is directional electromagnetic (EM) method.

In this chapter, a comprehensive investigation is conducted on the use of directional LWD resistivity tools in geosteering, especially the application in detecting remote bed boundaries. By looking into the electromagnetic field of various tool configurations, an independent evaluation is provided on the downhole boundary detection capability of multiple types of resistivity logging tools, as well as their applicability in different drilling environments.
To explore the potential of predicting formation properties in front of the drill bit, tool responses are first modeled with different downhole electromagnetic transmitters in homogeneous formation, where the ahead-of-the-bit field distribution is investigated. Field attenuation rates are compared among different tools, and the influence of borehole conductivity is studied. Next, tool responses are modeled in two-layer formation models to evaluate their boundary detection capabilities. The look-ahead capabilities are compared between tools with axially symmetrical antennas, with boundaries perpendicularly approached by the tool. Also, cross-component measurements are studied for tools using orthogonal antennas with boundaries parallel with the tool axis. After that, the deep-looking capability of a new directional resistivity tool using ultralong spacings and low frequencies is explored. Tool responses for different configuration parameters and drilling environments are calculated and discussed. At last, an inversion algorithm based on the Gauss–Newton method is developed to invert the boundary distance from the tool response, which can be either applied in two-layer or three-layer formations.

This chapter addresses the challenge of using LWD resistivity tools to predict formation anomalies ahead of or around the drill bit. Through the simulation results, one can gain an organized knowledge on the characteristics of LWD tools in terms of boundary detection capability. The detailed comparison results between tools of different types establish a missing link in the research of deep resistivity tools, and provide an objective reference for future designs of downhole boundary detection methods. The investigation of the deep-looking directional resistivity tool has demonstrated that an ultralong detection range can be achieved with azimuthal sensitivity using frequency-domain excitation sources.

The rapid development of LWD technology made the geosteering possible. Based on the real-time data gathered with LWD tools, better-informed drilling decisions can be made to improve drilling efficiency as well as to reduce safety risks. Due to its electromagnetic nature, LWD resistivity tools typically have a longer detection range than that of other LWD tools (e.g., acoustic, gamma ray, nuclear magnetic resonance (NMR)), and hence play an important role in geosteering applications. With early detection of approaching bed boundaries, the operator can accurately control the drilling direction, steering the bit onto the optimal well path, or away from unwanted formation structures.

Many examples have shown that it is advantageous to detect a formation anomaly ahead of or around a drill bit, such as a bypassed reservoir, an overpressured zone, a fault, or a salt dome. However, for conventional LWD resistivity tools, the response is mainly contributed by the formation volume around the tool, and cannot directly “look ahead.” Payton et al. [1] proposed to use a transient electromagnetic method to detect boundaries. Unlike traditional resistivity logging tools which use frequency-domain excitation to generate electromagnetic field, the transient electromagnetic
method adopts a time-domain excitation, which employs pulse signals or other periodic waveforms as a source and measures the returned broadband response. This technique is able to detect formation anomalies up to a hundred meters away. Banning et al. [2] further explored the potential of applying this method in detecting formation anomalies ahead of and around the drill bit, measuring both of direction and distance information. By monitoring the temporal change of received voltage, one can separate the responses of different spatial areas, and the data in later time stages contain information of remote bed boundaries. Theoretically, the transient method is capable of providing information about formation anomalies ahead of the bit, but it would require complicated downhole sensors and advanced LWD telemetry method to transmit the large volume of data to the surface if used to assist geosteering operations. At the time of writing, transient electromagnetic tools have not yet been commercialized.

In frequency domain, the earliest possible measurement of the formation being drilled is provided by the Resistivity-at-the-Bit tool developed by Bonner et al. [3]. The concept of the tool is based on the earlier work by Gianzero et al. [4], replacing the traditional coil antennas of resistivity tools with toroidal transmitters. A low-frequency axial current is driven through the drill bit, into the formation, and then flows back to the collar. When the tool is mounted closely to the bit, this “at-the-bit” measurement can be used as a reference for geosteering, or rather, geostopping. Field tests show that this type of resistivity measurement is earlier than any other measurements, but the response still lags behind the actually drilled spot by several inches. Bittar et al. [5] proposed that ahead-of-the-bit boundaries can be indicated by the relative difference between measurements by multispacing toroidal transmitters. For coil tools, Zhou et al. [6] briefly discussed the electromagnetic field ahead of the drill bit in 2000, and investigated the deep-looking limits of frequency- and time-domain methods.

Although it is not common to directly measure the ahead-of-the-bit formation volume with resistivity logging tools, the look-ahead capability can be acquired in an indirect way. In highly deviated wells with nearby bed boundaries, if the tool can provide deep measurements to detect lateral boundaries, the apparent distance from the bit to the boundary can be calculated with a given dip angle, i.e., the “look-around” capability can be converted to a “look-ahead” distance. Therefore the deep-looking capability would benefit from the increase of the radial depth of investigation (DOI) for LWD tools used as a geosteering aid. This can be done by increasing the transmitter—receiver spacing and using lower frequencies, as is applied on the deep resistivity tool in Seydoux et al. [7]. This tool responds rather early to approaching boundaries, claiming a detection range of 30 m, but the measurements lack directionality due to the axial symmetry of antennas. To provide directional information, an LWD tool with azimuthal sensitivity was developed to assist geosteering practice [8].
This tool uses cross-component measurements to distinguish between the boundaries approached from above and below the tool, and claims to detect boundaries that are 10–15 ft away from the borehole. Until recently, a new ultradeep directional tool is developed achieving a detection range of up to 30 m [9], but the tool physics has not yet been disclosed.

The objective of this chapter is to conduct a comprehensive investigation on the use of LWD resistivity logging tools in geosteering, especially the application in detecting remote bed boundaries. By looking into the electromagnetic field of various tool configurations, an independent evaluation is performed on the downhole boundary detection capability of different resistivity logging tools and their applicability in various drilling environments.

From the EM theory, to look ahead is rather difficult. First of all, we have to generate a field that can reach the front of the drill bit, or, at least, have part of the EM energy reaching the formation ahead of the drill bit. In other word, the antennas installed on the drill collar must have some kind of directivity. As we know, the directivity of antennas is based on the superposition of the waves with different phases. For low-frequency EM field, making directional antennas are very difficult in a limited space since the wavelength is too long. The other way to “focus” the field is to use multiple electrodes on the drill collar and control the potentials at each electrode so that the current flow is pushed forward to the designed direction. This idea has been successfully implemented in the laterolog tools in wireline (and LWD) to focus the field into the radial direction. Unfortunately, there is no space to place any electrode in the drill string to focus the field in the direction of drilling. In the first part of this chapter, we will discuss the sources available for possible look-ahead tools. Then we will investigate how these sources and detectors perform for the look-ahead detection. Finally, we will study the directional tool configuration for geosteering applications.

### 11.2 Ahead-Of-The-Bit Field Distribution Of LWD Tools

From the previous chapters, we noticed that four different sources are used in EM logging: electrodes (laterolog, microresistivity imager), coils (induction tools, LWD resistivity), RF antennas (dielectric tools), and toroidal coils (near-bit resistivity). As we know, skin depth is the key to the detection range. Lower frequency will “see” further. Therefore only low-frequency tools are possible to penetrate through conductive formation and reach further. Although DC sources can be used as a source, the implementation will be difficult due to noise and DC bias shift in the receiver circuits. Therefore most DC logging tools use low-frequency AC instead.

Mostly used sources in the EM logging tools are coils. From previous chapters, we know that the coils are used in many different tools including induction, and LWD resistivity. The main reason we use coils in the logging tools is that coils fit the
geometry naturally. Although the electrical dipole may be used for transmitting sources, the geometry of electric dipoles are not convenient in fitting into the logging tools. From a circuit point of view, coils are inductors; when frequency is low, the impedance will be low and therefore, the coil antennas are used only at kilohertz to low megahertz range. At higher frequencies, the coils will have a self-resonant frequency, which makes the coil no longer stable as an inductor. In LWD tools, ferrites are added to the antennas to increase signal transmitting and receiving efficiency with a compromise in temperature stability since the magnetic permeability of the ferrites is a nonlinear function of temperature. Therefore, in order to overcome the temperature issue, most LWD tools have to use compensation method to remove the temperature instability caused by antennas and circuits.

Another choice of antenna for logging tools is toroidal antenna. Toroidal antenna has the geometry of a coil but equivalent to an electric dipole source as shown in Fig. 11.1. A resistivity logging tool with toroidal antennas was introduced by Gianzero et al. [4]. A toroidal antenna is a winding of loops of conductive wire around a ring of material with a high value of magnetic permeability. The concept of using toroidal transmitters and receivers for induction logging was first proposed by Arps [10]. An alternating current flows through the wire to generate an alternating magnetic field inside the torus, which in turn induce radial and axial currents in the surrounding formations. The induced current can flow along the conductive drill collar, and then form a return path in the formations. Using toroidal sensors, ring electrodes, or button electrodes as receivers, one can derive the formation conductivity from the voltage. A practical implementation of a toroidal antenna is shown in Fig. 11.1, where the counter windings can effectively minimize the $z$-direction magnetic dipole component. The core is usually made of either ferrite materials or mu-metal to increase radiation efficiency.

The toroidal tool added a new direction to resistivity logging and formation evaluation, and has shown its advantages when using conductive mud in highly resistive

![Figure 11.1](image-url)
formations. Further adaptations of toroidal tools are made to improve the reliability and accuracy of the resistivity measurements in Bonner et al. [3] and Bittar and Hu [11].

A toroidal antenna can be modeled as a magnetic current loop. Although magnetic current does not exist in the physical world, it can serve as an intermediate variable in analytical calculations.

Similar to the formulations of Chapter 2, Fundamentals of Electromagnetic Fields Induction Logging Tools, the solution to the field generated by a magnetic ring source can be obtained by using the duality theorem in electromagnetism (Section 3.2, Harrington, RF), Maxwell’s equations can be solved to find the field of a toroidal transmitter. For a magnetic current loop, the field generated is dual to the electrical current loop. In the spherical coordinates, the magnetic field generated by the electrical current loop in a cylindrical coordinates is given in Eq. (2.36):

$$E_\phi = \frac{-j\omega \mu I_T A_T N_T}{4\pi} \frac{\rho e^{-jk\sqrt{\rho^2+z^2}}(1 + jk\sqrt{\rho^2+z^2})}{(\rho^2+z^2)^{3/2}}$$

(2.36)

Converting the expression to the spherical coordinates, we have

$$E_\phi = \frac{\omega \mu I_A T N_T}{4\pi r} \frac{k}{e^{-jkr}} \left(1 - \frac{j}{kr}\right) \sin (\theta)$$

(11.1a)

The magnetic components of the current loop can also be found directly from the $E$ field expression:

$$H_r = \frac{IA_T N_T}{2\pi r^2} e^{-jkr} \left(j + \frac{1}{rk}\right) \cos (\theta)$$

(11.1b)

$$H_\theta = \frac{IA_T N_T}{4\pi r} e^{-jkr} \left(-k + \frac{j}{r} + \frac{1}{r^2}\right) \sin (\theta)$$

(11.1c)

Using the duality theorem for the magnetic current loop Eq. (11.1a,b,c) becomes

$$H_\phi(r) = \frac{\omega \mu k \gamma s}{4\pi r} e^{-jkr} \left(1 - \frac{j}{kr}\right) \sin (\theta)$$

(11.2a)

$$E_r(r) = \frac{I \gamma k}{2\pi r^2} e^{-jkr} \left(j + \frac{1}{rk}\right) \cos (\theta)$$

(11.2b)

$$E_\theta = \frac{IA_T N_T k}{4\pi r} e^{-jkr} \left(-k + \frac{j}{r} + \frac{1}{r^2}\right) \sin (\theta)$$

(11.2c)
after the duality substitutions are applied, where \( \gamma_s = N_T I_T A_T \cdot \Delta A_T \) is the moment of the toroidal antenna. Here \( \Delta A_T \) is the cross-sectional area, and \( A_T \) is the area which is limited by the central line of the toroidal antenna, as illustrated in Fig. 11.2. Using a similar toroidal receiver along tool axis, the induced voltage can be expressed by

\[
V = j \omega \mu N_R H_0 \Delta A_R
\]

where \( \Delta A_R \) is the cross-section area of the toroidal receiver.

In numerical modeling, a toroidal transmitter can also be modeled as an insulating gap, as illustrated in Fig. 11.3. The tool is separated into two parts, with an alternating voltage source connecting to both sides of an imbedded insulator. Such a gap structure has been seen in LWD telemetry, used to transmit data from downhole equipment to the surface.

Fig. 11.4 shows the field distribution near the transmitter antenna when toroids are used in both water-based mud (WBM) and oil-based mud (OBM). We can clearly see that \( E \) field actually goes into the formation in the front of the drill bit. An 8.5-in. borehole is included in the model, filled with two types of mud: WBM of conductivity 10 S/m (resistivity 0.1 ohm-m) and OBM of conductivity 0.001 S/m (1000 ohm-m). From Fig. 11.4, we can see that in the OBM case, the most field does not go into the formation in the radial direction; instead the field is pushed along the drill string and to
the front of the drill bit. However, in the WBM case, the field has more energy going into the formation radially.

As shown in Fig. 11.3, theoretically, the toroid antenna is equivalent to the gap around the drill collar. Figs. 11.5 and 11.6 show the $E_z$ field ahead of the drill bit with a gap antenna in different formation conductivities and when borehole mud is WBM and OBM. We can see that the field attenuation reduces when the resistivity of the formation increases.
11.3 TOROIDAL TRANSMITTER

For a resistivity tool using a toroidal transmitter, several types of receiver can be used: toroidal receiver, ring electrode, and button electrode. Fig. 11.7 shows the current distribution of a toroidal transmitter in a homogeneous medium. Both radial and axial currents can be measured and used to calculate the formation resistivity. The axial currents can be measured by a single toroidal receiver similar to the transmitter as discussed in Section 11.1, or by using a pair of toroidal receivers and taking a voltage difference [4]. If the transmitter is close to the bit face, the bit can be seen as an electrode, conducting the currents into the formation ahead. The effective bit electric length depends on the formation conductivity and the collar resistivity, and can be extended by a conductive borehole [3].

The axial currents on the drill collar can be measured by a ring electrode or a button electrode. The electrodes are insulated from the drill collar but held at the same potential with the collar so that the original current distribution is not disturbed. The button electrode has an azimuthal sensitivity, while the ring electrode provides an azimuthally average measurement. The button electrodes are widely used for borehole resistivity imagings. Due to the fact that the drill collar can be rotating, LWD resistivity imagers provide continuous borehole coverage that captures near-wellbore information. The detailed discussions of the imaging tools will be given in Chapter 15, Laterolog Tools and Array Laterolog Tools, of this book.
To investigate the sensitivity of a toroidal system to the formation change in front of a drill bit, a numerical model is established. Fig. 11.8 shows the configuration of the toroidal tool used in the modeling. A toroidal transmitter is modeled as a magnetic current around the drill string, and two toroidal receivers are situated above the
transmitter, measuring the axial currents flowing along the collar. For comparison, a button electrode is also used to measure the radial currents flowing out of the drill string. The button electrode is in the middle between the two toroidal receivers. The transmitter–receiver spacing $L$ is defined as the distance between the button electrode and the transmitter.

A dynamic meshing approach is used similar to the modeling of coil tools. As the conductive boundary moves toward the tool, the azimuthal magnetic field $H_\phi$ at the toroidal receivers and the radial current density $J_r$ at the button electrode are measured. The apparent resistivity can be transformed either from the magnetic field difference of the two receivers, or from the radial current.

Figs. 11.9 and 11.10 show the responses of the tool with four different spacings: 12, 20, 32, and 40 in. The distance between the two toroidal receivers is 8 in. Measurements are acquired at 10 kHz. A two-layer formation model is used, with a local bed resistivity 10 ohm-m, and a 1-ohm-m bed boundary perpendicular to the tool axis, i.e., the formation conductivity contrast $\lambda = 10$. The results show that measurements provided by the toroidal receiver pair and the button electrode are very similar. This equivalence can be explained by the relationship of the axial and radial currents. If the axial currents at the lower and upper toroidal receivers are $I_{z_1}$ and $I_{z_2}$, respectively, and the radial current flowing off the drill string from the area between the two receivers is $I_r$, the following equation holds [5]:

$$I_r = I_{z_1} - I_{z_2}$$ (11.4)
The results also demonstrate that the tool response is not very sensitive to the spacing change. For the 10-kHz tool with 40-in. spacing, the look-ahead distance is about 0.11 m when the resistivity drops from 10 to 9.5 ohm-m. Note that for 10-kHz coil tools, the response is much lazier. The 5% resistivity threshold cannot be reached even when the bit hits the boundary. From this perspective, the toroidal tool gives an earlier response to ahead-of-the-bit boundaries than traditional coil tools.

Fig. 11.11 shows the tool response at three different operating frequencies: 10, 20, and 50 kHz. The transmitter—receiver spacing is 32 in. Due to the equivalence of the toroidal receiver and button electrode measurements, here only the button electrode response, i.e., the radial current resistivity, is plotted. The data show that the sensitivity to the boundaries ahead improves as the frequency increases, but does not benefit as much as coil tools. At 50 kHz, the detection range is about 0.18 m.

Fig. 11.12 shows the influence of the formation conductivity contrast on the tool response. The local-layer resistivity remains at 10 ohm-m, while the ahead-of-the-bit boundary resistivity is set to 1, 0.5, and 0.2 ohm-m. Compared with coil tools, formation conductivity contrast barely affects the tool response. For a 20-kHz toroidal tool with 32-in. spacing, when λ changes from 10 to 50, the detection range only increases from 0.13 to 0.17 m.

As a summary, the look-ahead response of toroidal tools is not very sensitive to the adjustment of tool configuration. Once the operating frequency of the transmitter is determined, the tool response is relatively steady. The improvement of detection range by increasing the transmitter—receiver spacing and formation conductivity contrast is
not very obvious as what we observe on coil tools. For lower frequencies and lower formation conductivity contrasts, the sensitivity of the coil tools is not sufficient to identify approaching boundaries, while toroidal tools show an earlier response on resistivity logs. For coil tools, the sensitivity to formation conductivity contrast makes it possible to predict the bed conductivity before the bit penetrates the layer ahead,
given that the boundary positions are preacquired and adequately accurate. On the other hand, if the boundary approached by the bit is unexpected, the distance inverted from toroidal tool responses should be more reliable.

Fig. 11.13 shows the response of a 20-kHz, 32-in. toroidal tool in the same two-layer formation model but with a borehole included. The borehole is filled with WBM ($R_m = 0.1$ ohm-m). As discussed previously, the WBM-filled borehole is beneficial for the look-ahead capabilities of toroidal tools in homogeneous formations, since the ahead-of-the-bit field attenuation is weaker with the existence of conductive mud. However, Fig. 11.13 demonstrates that the tool response is not very sensitive to borehole conductivity change in terms of boundary detection. Compared with the case where no borehole is included, the detection range defined by a 5% resistivity drop increases from 0.13 to 0.17 m with a conductive borehole.

11.4 BOUNDARY DETECTION USING ORTHOGONAL ANTENNAS

With the advancement of directional drilling technology, many wells are now designed with high angles or horizontally. In this way, production can be maximized in thin pay zones, making the drilling procedure more economic. For induction tools using coaxial antennas, the detection sensitivity of horizontal boundaries is closely related to the radial DOI of the tool, and has been well discussed [12,13]. For normal LWD tools, the radial detection range is generally a few feet. In this section, the tool
response with orthogonal antennas is investigated to explore its horizontal boundary detection capabilities.

First, the response of a tool using an axial toroidal transmitter and a transverse coil receiver is studied. A three-dimensional (3D) model is built in COMSOL, illustrated in Fig. 11.14. The transmitter is modeled as a unit-magnitude electric dipole in $z$ direction. In homogeneous media, the generated magnetic field is in $\varphi$ direction, so the magnetic field measured by the $y$-direction coil $H_y$ is zero. With the existence of a boundary which is parallel with $XZ$ plane, $H_y$ is no longer zero, and hence can be used as an indicator to the boundary distance.

Fig. 11.15 shows the tool response as the boundary moves toward the tool. The local layer is 10 ohm-m, and the target layer is 1 ohm-m. Two transmitter—receiver spacings are used: 20 and 32 in. Measurements are acquired at 20 kHz. The results
show that the received voltage responds to the boundary at a relatively early position. With a detection threshold of 2 μV, the detection range for 20 in. is about 1.0 m. However, the response is not a monotonic function of the distance to the boundary. As the conductive layer approaches, the voltage first increases, and then drops down after a peak value is reached. This phenomenon can be observed from the $H_y$ distribution plotted in Fig. 11.16, where the white arrow represents the direction of magnetic field on the $x = 0$ plane. When the boundary is relatively far from the tool, the $H_y$ field has an elliptical shape, as shown in the left figure. However, if the tool is too close to the boundary, the middle part of the field becomes narrower, resembling a spindle-torus shape. From Fig. 11.15, one can also see that the short-spacing signal is stronger and more sensitive to the distance, since the propagation attenuation is lower.

A second model is illustrated in Fig. 11.17. The tool uses an axial coil transmitter, which is modeled as a unit-magnitude magnetic dipole, and a transverse coil receiver in $x$ direction. In homogeneous formations, the cross components $H_x$ and $H_y$ should be zero. However, with a boundary that is parallel with the $YZ$ plane existing...
in proximity, the magnetic field $H_x$ is no longer zero and can be used as an indicator of the boundary-to-tool distance.

Fig. 11.18 shows the voltage measurement of the $x$-directed coil as the boundary position changes. The same two-layer model is used, and the tool also operates at 20 kHz. The results show that the response monotonically increases as the boundary moves toward the tool. With the same 2-μV voltage threshold, the detection range is about 0.65 m, which appears to be shorter than the previous model. However, the monotonicity of the response reduces the uncertainty of distance inversion, which is desired in geosteering operations. To take advantage of this monotonic feature, one can increase the signal strength by increasing the number of coil turns to reach a certain detection threshold.

As a summary, we can see that the look-ahead capability of coil and toroidal tools investigated in a formation model where the boundary is perpendicular to the tool axis have some capability in detecting boundaries in the front of the drill bit. The results have shown that with axially symmetrical antennas, the ability of detecting boundaries ahead of the bit is very limited. For a 20-kHz coil tool, a detection range of 0.33 m can be reached under favorable conditions, while a toroidal tool typically detects up to 0.17 m. It is also observed that the coil tool response is easily affected by formation conductivity contrast $\lambda$. When $\lambda$ is not high enough, the sensitivity is rather low and cannot indicate boundaries ahead. On the other hand, the response of toroidal tools is relatively independent of $\lambda$. If the conductivity of the approaching boundary is uncertain, the toroidal tool response can be relied on to reduce the ambiguity brought by different boundary conductivities.

From the 3D model built for exploring the feasibility of detection horizontal boundaries with orthogonal antennas shows that the orthogonal antennas are promising.
The results show that for both coil and toroidal transmitters, the voltage received by a transverse receivers can be used to indicate an approaching horizontal boundary. However, for toroidal transmitters, the response is not monotonic, which may cause problems in distance inversion. Therefore it is more beneficial to detect horizontal boundaries with coil tools using orthogonal antennas.

11.5 DEEP-LOOKING DIRECTIONAL RESISTIVITY TOOL

As analyzed in the previous sections, the LWD resistivity tools have some look-ahead capabilities. However the direct look-ahead capability is greatly limited by the geometry of the cylindrical tool structure. It is almost impossible to place antenna arrays over the cross section of the drill bit. However, as we discussed in the previous sections, the LWD resistivity tools are sensitive to the boundaries on the side of the tool. We know that the DOI is largely dependent on the operating frequency (skin depth) and transmitter–receiver spacing. The cross component of the tool is sensitive to the boundaries on the side. If we build a tool, that has (1) long T-R spacing; (2) cross-component measurement; (3) low frequency, this tool may be used to detect side formation boundaries far from the tool. In this section, we will discuss the performance of such long detection LWD tool.

Traditional LWD resistivity tools use transmitters and receivers that have the same polarization. As discussed in the previous chapters, a generic LWD tool consists of at least one transmitter coil and two receiver coils, and calculates amplitude ratio and phase difference of the induced voltage at the two receivers. Commercial tools are usually equipped with an array of antennas in order to take measurements with different DOIs at the same time, and operate at multiple frequencies, too. The operating frequency of LWD tools is usually higher (400 kHz–2 MHz) than that of wireline induction tools (10–120 kHz), which overcomes the effects brought by the metal tool body, making the DOI of LWD tools comparable with induction tools (2–5 ft).

Due to its electromagnetic nature, LWD resistivity tools can reach much further distance than other LWD tools (e.g., gamma ray, NMR, etc.), and hence become critical in making real-time decisions for such applications. In highly deviated wells where the tool is not strictly parallel to the formation boundaries, the capability of detecting a boundary around the tool can be leveraged to predict the ahead-of-the-bit distance to the boundary. As shown in Fig. 11.19, if the look-around distance \( D_{ar} \) and the relative formation dip \( \alpha \) can be obtained, the look-ahead distance \( D_{ah} \) can be expressed by

\[
D_{ah} = \frac{D_{ar}}{\tan \alpha} - D_{tb}
\]

(11.5)

where \( D_{tb} \) represents the distance from transmitter coil to the drill bit. Since \( D_{ar} \) is a function of the radial DOI, such pseudo look-ahead capability can be enhanced by expanding the DOI of LWD tools.
In 2003 an ultradeep LWD tool was proposed to facilitate reservoir navigation applications [7]. Operating at lower frequencies (2, 10, and 100 kHz), the radial response of the tool is much larger than traditional LWD tools. The transmitters and receivers are manufactured on individual subs, so that in theory they could be placed anywhere behind the drill bit. In a case where two transmitter and one receiver subs are used, and the distances between the transmitters and the receiver are around 21 and 11 m, respectively, a detection range of tens of meters is reported in field tests.

However a major disadvantage of this type of tools is that it lacks azimuthal directionality. Due to the axial symmetry of the tool configuration, the resistivity measurement taken by coaxial antennas is an average value reflecting the properties of the bulk formation volume around the borehole. Any anomalies that are in the way of the eddy currents induced in the formation will affect the tool response, in spite of the azimuthal direction in which they are located.

As shown in Figs. 11.20 and 11.21, a 36-in., 400-kHz propagation tool approaches the boundary with the same relative dip angle $\alpha = 60$ degrees, while the azimuthal positions of the boundary are 180 degrees different. The tool responses are exactly the same. This axisymmetric feature might be acceptable in formation evaluation, but can be problematic in geosteering applications. To make steering decisions (to drill upward or downward) with this type of tools, some related geological knowledge must be obtained beforehand (e.g., the existence of an oil–water contact).

### 11.5.1 Physics of the directional resistivity tool

Inspired by wireline triaxial induction tools, multicomponent measurements are also integrated by LWD tools. With transverse or tilted coil antennas as receivers, an azimuthal sensitivity can be obtained, which is beneficial for geosteering applications [8].

The azimuthal sensitivity of a 36-in., 400-kHz tool with an axial coil transmitter and a transverse coil receiver is illustrated in Fig. 11.22. The tool response is denoted as the cross component $H_{zx}$, with the subscript $z$ representing the $z$-direction transmitter, and $x$ the transverse receiver. In a homogeneous formation, there is no $x$-direction magnetic field. With the existence of a boundary nearby, $H_{zx}$ measures a nonzero value, which can be used as an indicator of boundary detection.

To simulate the tool response in Fig. 11.22, the tool is placed in a resistive formation bed of 10 ohm-m, parallel with a conductive bed of 1 ohm-m. The distance...
between the tool and the boundary remains constant. While the tool rotates with the transverse receiver pointing to different angles, both the real part (blue line (dark gray in print versions)) and the imaginary part (red line (light gray in print versions)) of $H_{zx}$ varies as a function of $\cos \phi$, where $\phi$ represents the azimuth angle. This means in the two scenarios illustrated by Fig. 11.23, where the boundary locates at a certain distance above and below the horizontal tool, the tool responses will show different signs. This nice feature is obviously beneficial for steering purposes. With adequate detection range, real-time drilling decisions can be made based on these measurements.

LWD tools with tilted coil antennas have similar benefits as transverse antennas do. A tilted coil points neither along the tool axis nor sideways, but is mounted with a certain angle (typically 45 degrees). The implementation of transverse and tilted coils can both be realized with slots on the tool, and covered by specialized shields, as
shown in Fig. 11.24 [14]. While the drilling string rotates, azimuthal measurements can be acquired by the receivers.

The directional measurements taken by tilted coil receivers actually result from the sign change of the cross component \( H_{zx} \), as discussed above. The only difference is that \( H_{zz} \) is also involved here. As shown in Fig. 11.25, the magnetic field received at the tilted antenna can be seen as a synthesis of both \( H_{zx} \) and \( H_{zz} \), and can be expressed by

\[
H_{up} = H_{zx} \sin \varphi + H_{zz} \cos \varphi
\]  

(11.6)
Figure 11.22 Azimuthal sensitivity of $H_{zx}$ for a 36-in., 400-kHz tool with a horizontal boundary. $\lambda = 10$.

Figure 11.23 Boundary above (A) and below (B) the transverse coil receiver.

Figure 11.24 (A) Tilted coil and (B) transverse coil shielded with slots [14].
and

\[ H_{\text{down}} = -H_{zx} \sin \varphi + H_{zz} \cos \varphi \]  

(11.7)

where \( \varphi \) is the angle between the receiver coil axis and the tool axis.

Therefore the directional measurements (amplitude ratio and phase shift) can be calculated from

\[
\frac{H_{\text{up}}}{H_{\text{down}}} = \frac{H_{zz} \cos \varphi + H_{zx} \sin \varphi}{H_{zz} \cos \varphi - H_{zx} \sin \varphi} = 1 + \frac{2H_{zx} \sin \varphi}{H_{zz} \cos \varphi - H_{zx} \sin \varphi} 
\]

(11.8)

The directional resistivity tools provided by service companies proved to be useful in many field tests. However, with the normal LWD frequency and tool spacing, these tools can only detect up to 21 ft. Deeper detection range cannot be reached with such tool configuration.

Since 2010, a new deep-looking tool was developed and reported to have the capability of detecting up to 30-m boundaries [9]. It has the azimuthal sensitivity as the directional resistivity tools do, but the detailed physics has not been disclosed yet.

### 11.5.2 Forward modeling of a deep-looking tool with tilted antennas

For induction tools, it is well known that DOI is a function of spacing and the skin depth. This rule applies to LWD directional resistivity tools as well. To reach a further boundary, a lower frequency and a longer distance between transmitters and receivers must be adopted. Based on the principles of the directional resistivity tool, the responses are simulated for lower frequencies and with longer spacings, and it proved to be effective in detecting further boundaries.

The forward modeling of the tool is based on a computer code named TRITI2011_series [15]. It analytically calculates the response of triaxial induction tools in one-dimensional multilayered formations. Using Eqs. (11.6)–(11.8), we can simulate the response of a tilted coil receiver and obtain the directional measurements.

First, the influence of spacing and frequency is investigated using a horizontal tool with a tilted coil antenna. As illustrated in Fig. 11.26, a three-layer formation model was used, with the middle layer having a resistivity of 10 ohm-m, and the conductive shoulder beds are 1 and 2 ohm-m, respectively.
The results are shown in Figs. 11.27—11.29. The resistive middle layer is 200 ft thick. The tool starts from 100 ft above the 1-ohm-m boundary, and ends at 100 ft below the 2-ohm-m boundary, remaining parallel with the boundaries at all times. Four different spacings are used: 5, 10, 20, and 30 m. The operating frequencies are 5, 2, and 1 kHz.
Both attenuation ratio and phase shift measurements can be used to detect approaching boundaries. Once the tool reaches the resistive zone, the signs of the responses can generally indicate whether the boundary is approaching from above or below. With a certain threshold (e.g., 0.05 dB for attenuation ratio, 0.15 degrees for phase shift), one can define a maximum detection range for the tool.

The responses are functions of spacing, frequency, and formation conductivity contrast. Long-spacing measurements usually show a larger detection range. For 2-kHz frequency and 20-m spacing, the tool can detect boundaries that are around 100 ft away (Fig. 11.28). However, in thinner layers, such responses may be affected by both shoulder beds and hence pose challenges for interpretation. In that case, shorter spacing measurements would be more reliable. In practice, multispacing measurements are recommended to adapt to different formation thicknesses.

Although lower frequencies seemingly expand the detection range, the signal amplitude of the responses decreases accordingly, especially for attenuation ratio. This feature calls for a trade-off in practical tool configuration.

Figure 11.28 Deep-looking responses of a 2-kHz frequency tool when crossing a 200-ft bed. Resistivity from left to right: 1, 10, 2 ohm-m.
Figs. 11.30 and 11.31 plot the responses of the same spacing, but with different operation frequencies. While the tool is within the resistive layer, the monotonicity of the signal depends on the product of wave number $k$ and spacing $L$, where $k$ can be written as

$$k = (1 - j) \frac{1}{\delta}$$  \hspace{1cm} (11.9)$$

Here $\delta$ is the skin depth that can be expressed by

$$\delta = \sqrt{\frac{2}{\omega \mu \sigma}}$$  \hspace{1cm} (11.10)$$

If $L$ is too long, or either of frequency and conductivity is too high, the tool response loses its monotonicity and becomes complicated to interpret. Therefore frequency and spacing should be carefully selected in practical tool design.
Figure 11.30 Deep-looking responses of a 20-m tool when crossing a 200-ft bed. Resistivity from left to right: 1, 10, 2 ohm-m.

Figure 11.31 Deep-looking responses of a 30-m tool when crossing a 200-ft bed. Resistivity from left to right: 1, 10, 2 ohm-m.
Fig. 11.32 plots the tool responses at the 1-ohm-m boundary. As the spacing goes up, the amplitude of the high-frequency responses are more easily affected by the decreasing skin depth (especially for the phase shift measurements), while the lower frequency responses remain monotonically increasing.

Figs. 11.33—11.35 further illustrate the influence of bed thickness. The middle layer starts from 100 ft, and ends at 200, 150, and 120 ft. The results show that if the bed is much shorter than the detection range of a particular tool configuration, the tool response is affected by both shoulder beds, and the sign of the signal may not be a reliable indicator of boundary location. An accurate interpretation will rely on a full inversion for boundary distance.
11.6 DISTANCE INVERSION BASED ON THE GAUSS–NEWTON ALGORITHM

11.6.1 Summary of Gauss–Newton Method

To determine the boundary distances from the responses of the deep-looking tool, the inversion algorithm discussed in Chapter 9, Theory of Inversion for Triaxial Induction and Logging-While-Drilling Logging Data in One- and Two-Dimensional Formations and Chapter 10, The Application of Image Theory in Geosteering, based on the Gauss–Newton method is used. As described in Chapter 9, Theory of Inversion for Triaxial Induction and Logging-While-Drilling Logging Data in One- and Two-Dimensional Formations and Chapter 10, The Application of Image Theory

Figure 11.33 Deep-looking responses for 2-kHz frequency when crossing a 100-ft bed. Resistivity from left to right: 1, 10, 2 ohm-m.
in Geosteering, Gauss–Newton algorithm is a method to find a minimum of a function, which is usually the difference function between real measurements and analytical results calculated from models, by computing first-order derivatives. Detailed formulations are given in Chapter 9, Theory of Inversion for Triaxial Induction and Logging–While–Drilling Logging Data in One- and Two-Dimensional Formations and Chapter 10, The Application of Image Theory in Geosteering, a summary of the equations used in for this purpose can be summarized as follows.

The Gauss–Newton method iteratively searches for a minimum of the sum of the squares

\[
S(\beta) = \sum_{i} r_{i}^{2}(\beta)
\]  

(11.11)

Figure 11.34 Deep-looking responses for 2-kHz frequency when crossing a 50-ft bed. Resistivity from left to right: 1, 10, 2 ohm-m.
where

\[ r_i(\beta) = y_i - f_i(\beta) \]  (11.12)

is the residue function, and

\[ \beta = (\beta_1, \beta_2, \ldots, \beta_n) \]  (11.13)

is the desired variable vector. To obtain a converged solution, \( m \) must be larger or equal to \( n \).

With an initial guess \( \beta^{(0)} \), the iteration process can be expressed by

\[ \beta^{(k+1)} = \beta^{(k)} + (J_f^TJ_f)^{-1}J_f r \]  (11.14)
where

\[
J_f = \frac{\partial f_i(\beta_i^{(k)})}{\partial \beta_i}
\]  

(11.15)

is the Jacobian matrix of the function \( f \).

### 11.6.2 Inversion in two-layer formations

First, a two-layer formation model is used, where the conductivities of both layers are assumed to be known, and only the distance to the boundary is inverted. The tool remains parallel to the boundary.

The residual function here can be expressed by

\[
r = \begin{pmatrix} r_1 \\ r_2 \end{pmatrix} = \begin{pmatrix} y_{At} - f_{At}(d) \\ y_{PS} - f_{PS}(d) \end{pmatrix}
\]  

(11.16)

where \( f_{At}(d) \) and \( f_{PS}(d) \) are the attenuation ratio and the phase shift responses calculated from the forward model, and \( y_{At} \) and \( y_{PS} \) are the actual measurements. The Jacobian matrix here is represented by

\[
J_f = \begin{pmatrix} f'_{At}(d^{(k)}) \\ f'_{PS}(d^{(k)}) \end{pmatrix}
\]  

(11.17)

where

\[
f'_{At}(d^{(k)}) = \frac{f_{At}((1 + \Delta)d^{(k)}) - f_{At}(d^{(k)})}{\Delta d^{(k)}}
\]  

(11.18)

and

\[
f'_{PS}(d^{(k)}) = \frac{f_{PS}((1 + \Delta)d^{(k)}) - f_{PS}(d^{(k)})}{\Delta d^{(k)}}
\]  

(11.19)

The inversion algorithm was tested for the four scenarios depicted in Fig. 11.36. The same conductivity difference \( \lambda = 10 \) was applied in all four cases, with the resistive layer representing a hydrocarbon reservoir, the conductive layer a shale bed above or the OWC below. Fig. 11.36A and B captures two typical cases for reservoir navigation in a thick bed, while Fig. 11.36C and D could happen if the original resistive target was missed, for which the tool response is also worth investigating.

The inversion results for a horizontal tool with 5-kHz frequency and 20-m spacing are listed below. The initial guess for boundary distance was 10 ft in most cases except for those with a different \( d^{(0)} \) mentioned under “remarks.” The increment is set as \( \Delta = 10^{-4} \), and the iteration ceases when \( d^{(k+1)} - d^{(k)} < 0.5 \text{ ft} \).
Tables 11.1 and 11.2 show the inversion results when the tool is in the 10-ohm-m layer. In most of its detection range, the inversion algorithm works very well, with the relative error below 1%. However, with the tool very close from the boundary, a change of initial guess is needed to obtain the desired results. This is because the Gauss–Newton method stops searching whenever a stationary point of $S$ is met, which could be the result from a local extremum.

Figure 11.36 Two-layer models used for inversion. (A) Tool is in high resistivity layer and the conductive boundary is above; (B) Tool is in high resistivity layer and the conductive boundary is below; (C) Tool is in low resistivity layer and the resistive boundary is below; (D) Tool is in low resistivity layer and the resistive boundary is above.

Table 11.1 Two-layer inversion results for 5-kHz frequency, 20-m spacing tool in resistive layer (conductive boundary above)

<table>
<thead>
<tr>
<th>Distance (ft)</th>
<th>Number of iterations</th>
<th>Inverted distance (ft)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>3</td>
<td>4.9998</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>3</td>
<td>15.0015</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>5</td>
<td>30.0000</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>6</td>
<td>49.9993</td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>5</td>
<td>75.0008</td>
<td></td>
</tr>
<tr>
<td>85</td>
<td>6</td>
<td>85.0026</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>7</td>
<td>99.9989</td>
<td></td>
</tr>
</tbody>
</table>

Table 11.2 Two-layer inversion results for 5-kHz frequency, 20-m spacing tool in resistive layer (conductive boundary below)

<table>
<thead>
<tr>
<th>Distance (ft)</th>
<th>Number of iterations</th>
<th>Inverted distance (ft)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>6</td>
<td>4.9791</td>
<td>$d^{(0)} = 10$</td>
</tr>
<tr>
<td>15</td>
<td>3</td>
<td>14.9994</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>5</td>
<td>30.0013</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>4</td>
<td>49.9985</td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>6</td>
<td>74.9993</td>
<td></td>
</tr>
<tr>
<td>85</td>
<td>7</td>
<td>85.0090</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>9</td>
<td>100.0005</td>
<td></td>
</tr>
</tbody>
</table>

Tables 11.1 and 11.2 show the inversion results when the tool is in the 10–ohm-m layer. In most of its detection range, the inversion algorithm works very well, with the relative error below 1%. However, with the tool very close from the boundary, a change of initial guess is needed to obtain the desired results. This is because the Gauss–Newton method stops searching whenever a stationary point of $S$ is met, which could be the result from a local extremum.
When the tool is close to the boundaries, inversion results can be affected by the multivalued attribute of the tool responses as discussed in previous sections, and converge to a different distance, which may lead to similar responses. On the other hand, if the tool is too far away from the boundary in which the signal is rather weak, the iteration becomes slow and may lead to unreliable results as well.

Tables 11.3 and 11.4 show the inversion results when the tool is in the 1-ohm-m layer. Compared with the two cases above, the multivalued problem appeared at a closer distance, where the initial guess of distance had to be changed to find the expected solution. Due to the high conductivity, the skin depth is relatively short in the 1-ohm-m formation. When the distance is beyond 75 ft from the boundary, the responses are rather weak, which makes the single-valued solution more difficult to obtain.

In practice, the initial guess of the distance could be adjusted with reference to other available information, such as geological maps, depth measurements, and other types of logs. Another solution is to integrate multispacing, multifrequency responses into the inversion process. In that way, the ambiguity caused by possible multivalued problems could be removed.

Table 11.3 Two-layer inversion results for 5-kHz frequency, 20-m spacing tool in conductive layer (resistive boundary below)

<table>
<thead>
<tr>
<th>Distance (ft)</th>
<th>Number of iterations</th>
<th>Inverted distance (ft)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>4</td>
<td>4.9780</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>3</td>
<td>14.9999</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>5</td>
<td>29.9996</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>3</td>
<td>50.0115</td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>4</td>
<td>74.9842</td>
<td>$d^{(0)} = 50$</td>
</tr>
<tr>
<td>85</td>
<td>8</td>
<td>84.9995</td>
<td>$d^{(0)} = 50$</td>
</tr>
<tr>
<td>100</td>
<td>10</td>
<td>90.4007</td>
<td>$d^{(0)} = 50$</td>
</tr>
</tbody>
</table>

Table 11.4 Two-layer inversion results for 5-kHz frequency, 20-m spacing tool in conductive layer (resistive boundary above)

<table>
<thead>
<tr>
<th>Distance (ft)</th>
<th>Number of iterations</th>
<th>Inverted distance (ft)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>4</td>
<td>4.9894</td>
<td>$d^{(0)} = 20$</td>
</tr>
<tr>
<td>15</td>
<td>3</td>
<td>15.0002</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>3</td>
<td>29.9999</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>3</td>
<td>50.0103</td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>5</td>
<td>74.9871</td>
<td></td>
</tr>
<tr>
<td>85</td>
<td>8</td>
<td>84.9849</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>3</td>
<td>100.0013</td>
<td>$d^{(0)} = 90$</td>
</tr>
</tbody>
</table>
To validate this statement, the inversion algorithm is modified with four log inputs, so the residual vector can be expressed by

\[
r = \begin{pmatrix}
  r_1 \\
  r_2 \\
  r_3 \\
  r_4
\end{pmatrix} = \begin{pmatrix}
  y_{\text{Att}_1} - f_{\text{Att}_1}(d) \\
  y_{\text{PS}_1} - f_{\text{PS}_1}(d) \\
  y_{\text{Att}_2} - f_{\text{Att}_2}(d) \\
  y_{\text{PS}_2} - f_{\text{PS}_2}(d)
\end{pmatrix}
\]  

(11.20)

where \(f_{\text{Att}_1}(d)\) and \(f_{\text{PS}_1}(d)\) represent the tool responses of the first frequency or spacing, and \(f_{\text{Att}_2}(d)\) and \(f_{\text{PS}_2}(d)\) the second. Combining responses of 20- and 30-m spacings, we repeated the experiments in Fig. 11.36A and D, where the multivalued problems appeared for near-boundary inversions. Results are shown in Tables 11.5 and 11.6, in which the initial guess was all set as 10 ft. Compared with Tables 11.1 and 11.4, one can see that the multivalued problem has been solved with little sacrifice on accuracy.

### 11.6.3 Inversion in three-layer formations

In this section, an inversion algorithm is developed for a three-layer formation model shown in Fig. 11.37. Assuming the tool is parallel to the boundaries, and all three bed resistivities are known, the Gauss—Newton method can be used to invert the distances to the two shoulder bed boundaries at the same time.

**Table 11.5** Two-layer inversion results for 5-kHz frequency, 20- and 30-m spacings combined tool in resistive layer (conductive boundary above)

<table>
<thead>
<tr>
<th>Distance (ft)</th>
<th>Number of iterations</th>
<th>Inverted distance (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>3</td>
<td>5.0001</td>
</tr>
<tr>
<td>15</td>
<td>3</td>
<td>14.9991</td>
</tr>
<tr>
<td>30</td>
<td>3</td>
<td>30.0009</td>
</tr>
</tbody>
</table>

**Table 11.6** Two-layer inversion results for 5-kHz frequency, 20- and 30-m spacings combined tool in conductive layer (resistive boundary above)

<table>
<thead>
<tr>
<th>Distance (ft)</th>
<th>Number of iterations</th>
<th>Inverted distance (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>3</td>
<td>4.9986</td>
</tr>
<tr>
<td>15</td>
<td>2</td>
<td>14.9989</td>
</tr>
<tr>
<td>30</td>
<td>5</td>
<td>29.9987</td>
</tr>
</tbody>
</table>

**Figure 11.37** Three-layer model used for inversion.
Since there are two variables, \( d_1 \) and \( d_2 \), we have

\[
\mathbf{\beta} = (d_1, d_2)
\]  

(11.21)

and

\[
\mathbf{r} = \begin{pmatrix} r_1 \\ r_2 \end{pmatrix} = \begin{pmatrix} \gamma_{Att} - f_{Att}(d_1, d_2) \\ \gamma_{PS} - f_{PS}(d_1, d_2) \end{pmatrix}
\]  

(11.22)

The Jacobian matrix becomes

\[
\mathbf{J}_f = \begin{pmatrix}
\frac{\partial f_{Att}}{\partial d_1} & \frac{\partial f_{Att}}{\partial d_2} \\
\frac{\partial f_{PS}}{\partial d_1} & \frac{\partial f_{PS}}{\partial d_2}
\end{pmatrix}
\]  

(11.23)

where

\[
\frac{\partial f_{Att}(d_1^{(k)}, d_2^{(k)})}{\partial d_1} = \frac{f_{Att}((1 + \Delta)d_1^{(k)}, d_2^{(k)}) - f_{Att}(d_1^{(k)}, d_2^{(k)})}{\Delta d_1^{(k)}}
\]  

(11.24)

\[
\frac{\partial f_{Att}(d_1^{(k)}, d_2^{(k)})}{\partial d_2} = \frac{f_{Att}(d_1^{(k)}, (1 + \Delta)d_2^{(k)}) - f_{Att}(d_1^{(k)}, d_2^{(k)})}{\Delta d_2^{(k)}}
\]  

(11.25)

\[
\frac{\partial f_{PS}(d_1^{(k)}, d_2^{(k)})}{\partial d_1} = \frac{f_{PS}((1 + \Delta)d_1^{(k)}, d_2^{(k)}) - f_{PS}(d_1^{(k)}, d_2^{(k)})}{\Delta d_1^{(k)}}
\]  

(11.26)

\[
\frac{\partial f_{PS}(d_1^{(k)}, d_2^{(k)})}{\partial d_2} = \frac{f_{PS}(d_1^{(k)}, (1 + \Delta)d_2^{(k)}) - f_{PS}(d_1^{(k)}, d_2^{(k)})}{\Delta d_2^{(k)}}
\]  

(11.27)

The inversion results for a horizontal tool with 2-kHz frequency and 20-m spacing are listed in Table 11.7. The initial guess for both \( d_1 \) and \( d_2 \) was 10 ft except for those mentioned under “remarks.” The increment is set as \( \Delta = 10^{-4} \), and the iteration ceases when \( d_1^{(k+1)} - d_1^{(k)} < 0.5 \) ft, and \( d_2^{(k+1)} - d_2^{(k)} < 0.5 \) ft.

The results show that the inversion algorithm is greatly affected by the multivalued attribute of the tool responses, and are sensitive to the initial guess of \( d_1 \) and \( d_2 \). To solve this problem, one can again combine multifrequency and multispacing responses as input variables, as discussed in the last section. Alternatively, it can be done by using the bed thickness of the middle layer, which could usually be acquired from geological maps, as a constraint, to help eliminate the nonuniqueness of inversion.

With known bed thickness of the middle layer, similar experiments to those in Table 11.7 are performed, and the results are listed in Table 11.8. Inversion at all points used the same initial guess for \( d_1 \) and \( d_2 \) (10 ft). Compared with Table 11.7, we can see that not only the nonuniqueness problem is solved, but the iteration process converges faster in most cases.
Table 11.7 Three-layer inversion results for 2-kHz frequency, 20-m spacing tool in middle resistive layer

<table>
<thead>
<tr>
<th>Distance to upper boundary (ft)</th>
<th>Distance to lower boundary (ft)</th>
<th>Number of iterations</th>
<th>Inverted distance to upper boundary (ft)</th>
<th>Inverted distance to lower boundary (ft)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>12</td>
<td>3</td>
<td>8.0001</td>
<td>11.9967</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>40</td>
<td>5</td>
<td>10.0028</td>
<td>40.0159</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>30</td>
<td>4</td>
<td>19.9863</td>
<td>29.9481</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>80</td>
<td>5</td>
<td>20.0003</td>
<td>79.9837</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>60</td>
<td>5</td>
<td>40.0110</td>
<td>60.0713</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>20</td>
<td>3</td>
<td>79.9664</td>
<td>19.9964</td>
<td></td>
</tr>
</tbody>
</table>

Table 11.8 Three-layer inversion results for 2-kHz frequency, 20-m spacing tool in middle resistive layer, with known bed thickness

<table>
<thead>
<tr>
<th>Distance to upper boundary (ft)</th>
<th>Distance to lower boundary (ft)</th>
<th>Number of iterations</th>
<th>Inverted distance to upper boundary (ft)</th>
<th>Inverted distance to lower boundary (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>12</td>
<td>2</td>
<td>8.0009</td>
<td>11.9991</td>
</tr>
<tr>
<td>10</td>
<td>40</td>
<td>1</td>
<td>10.0007</td>
<td>39.9993</td>
</tr>
<tr>
<td>20</td>
<td>30</td>
<td>3</td>
<td>20.0001</td>
<td>29.9999</td>
</tr>
<tr>
<td>20</td>
<td>80</td>
<td>2</td>
<td>20.0001</td>
<td>79.9999</td>
</tr>
<tr>
<td>40</td>
<td>60</td>
<td>4</td>
<td>39.9996</td>
<td>60.0004</td>
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<td>80</td>
<td>20</td>
<td>4</td>
<td>80.0046</td>
<td>19.9954</td>
</tr>
</tbody>
</table>

Table 11.9 Three-layer inversion results for 2-kHz frequency, 20-m spacing, 60-degree dip angle tool in middle resistive layer, with known bed thickness

<table>
<thead>
<tr>
<th>Distance to upper boundary (ft)</th>
<th>Distance to lower boundary (ft)</th>
<th>Number of iteration</th>
<th>Inverted distance to upper boundary (ft)</th>
<th>Inverted distance to lower boundary (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>40</td>
<td>1</td>
<td>9.9993</td>
<td>40.0007</td>
</tr>
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<td>30</td>
<td>3</td>
<td>20.0025</td>
<td>29.9975</td>
</tr>
<tr>
<td>20</td>
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<td>60</td>
<td>4</td>
<td>40.0015</td>
<td>59.9985</td>
</tr>
<tr>
<td>80</td>
<td>20</td>
<td>4</td>
<td>79.9989</td>
<td>20.0011</td>
</tr>
</tbody>
</table>

Note that the inversion algorithm developed here not only applies to horizontal wells, but can also be generalized to other dip angles. Table 11.9 shows an example where the tool is not parallel to the boundaries, but has a 60-degree angle. The inversion results are equivalently accurate and reliable.
11.7 CONCLUSIONS

LWD resistivity tools play an important role in geosteering practice. With real-time information about the formation anomalies in front of or around the bit, the operator is able to make better-informed decisions, making the drilling process more efficient and economic. In this chapter, a study is conducted on the boundary detection capabilities of LWD tools with different configurations. By modeling the tool responses with analytical and numerical simulations, a better insight is developed on the applicability of LWD tools in various drilling environments.

To evaluate the potential of predicting formation properties in front of the drill bit, tools with different downhole electromagnetic transmitters are first modeled in homogeneous formation, and the ahead-of-the-bit field distribution is investigated. For both coil and toroidal antennas, the field attenuation follows a similar pattern that is determined by formation resistivity and operating frequency, while the comparison results have shown that coil antennas have a lower attenuation rate with respect to distance from the bit. The borehole conductivity barely affects the performance of coil tool in terms of look-ahead capability, but the attenuation of toroidal transmitters can be significantly improved by using more conductive mud.

Simulation results in two-layer formation models have further shown different behaviors of coil and toroidal tools. First, the look-ahead ability is compared between tools using axially symmetrical antennas. In favorable conditions, a 20-kHz coil tool can detect boundaries 0.33 m away from the bit. The detection range of toroidal tools is shorter on average, typically about 0.17 m, but is rather independent of the drilling environment. If the formation conductivity contrast is too low, the response of a coil tool may not be sensitive enough to indicate an approaching boundary, while toroidal tools can still provide look-ahead responses. Next, horizontal boundary detection capability is tested with tools using orthogonal antennas. The results have demonstrated that such cross-component measurements can be used for boundary detection with both coil and toroidal antennas, but the response of coil tools is seen as a better indicator of boundary distance due to its monotonicity. Based on this observation, further investigations are conducted on the boundary detection capability of coil tools using multidirectional measurements.

It has been demonstrated that the deep-looking capability can be achieved by applying ultralong transmitter—receiver spacings and low frequencies to the directional resistivity tool using transverse or tilted receivers. For a 20-m, 2-kHz tool, boundaries that are approximately 100 ft away can be detected using the developed inversion algorithm. This work provides a new perspective for the research of resistivity logging tools. With the rapid advancement of modern drilling technology, LWD tools are expected to not only perform effective measurements around the wellbore, but also facilitate the drilling operations by predicting formation anomalies in advance. Based on the simulations, one can conclude that horizontal bed boundaries
can be best detected and located by ultralong, low-frequency tools using multidirec-
tional measurements, while the look-ahead capability of resistivity tools is rather lim-
ited with current frequency-domain excitation methods. To further expand the
detection range ahead of the bit, the transient electromagnetic method using time-
domain excitation sources may provide a solution for the next-generation LWD
resistivity tools.

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