(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
20 October 2011 (20.10.2011)

PCT

(10) International Publication Number
WO 2011/129828 A1

(51) International Patent Classification:
G01V 3/28 (2006.01)

(21) International Application Number:
PCT/US2010/031243

(22) International Filing Date:
15 April 2010 (15.04.2010)

(25) Filing Language: English

(26) Publication Language: English

(71) Applicant *(for all designated States except US)*: **HALLIBURTON ENERGY SERVICES, INC.** [US/US]; 10200 Bellaire Blvd., Houston, Texas 77072 (US).

(72) Inventors; and

(75) Inventors/Applicants *(for US only)*: **BITTAR, Michael S.** [US/US]; 8711 Wheatland Drive, Houston, Texas 77064 (US). **WU, Hsu-Hsiang** [CN/US]; 5530 Chesapeake Place, Sugar Land, Texas 77479 (US). **LI, Shanjun** [CN/US]; 2811 Grants River Circle, Sugar Land, Texas 77479 (US).

(74) Agents: **MADDEN, Robert B.** et al.; Schwegman, Lundberg & Woessner, P.A., P.O. Box 2938, Minneapolis, Minnesota 55402 (US).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PE, PG, PH, PL, PT, RO, RS, RU, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*

WO 2011/129828 A1

(54) Title: PROCESSING AND GEOSTEERING WITH A ROTATING TOOL

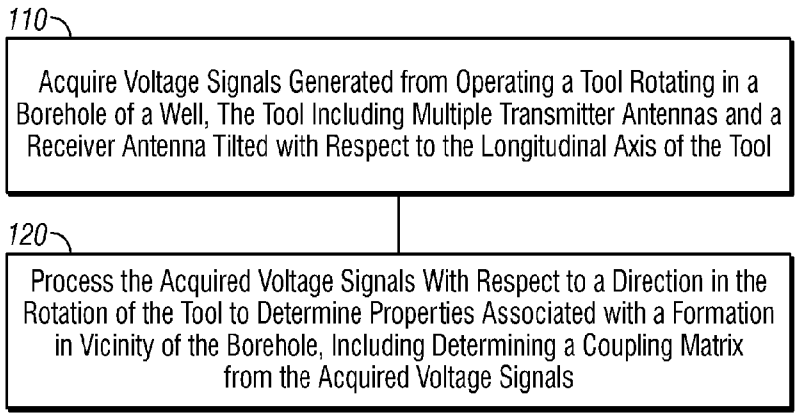


FIG. 1

(57) Abstract: Various embodiments include apparatus and methods of processing and geosteering with respect to well logging. Apparatus and methods may include acquiring signals generated from operating a tool rotating in a borehole of a well, where the tool includes a receiver antenna tilted with respect to the longitudinal axis of the tool and two transmitter antennas. The acquired signals can be processed with respect to a direction in the rotation of the tool to determine properties associated with a formation and/or to determine a geosignal for geosteering a drilling operation.

PROCESSING AND GEOSTEERING WITH A ROTATING TOOL

Technical Field

The present invention relates generally to systems having well logging capability.

Background

In drilling wells for oil and gas exploration, understanding the structure and properties of the geological formation surrounding a borehole provides information to aid such exploration. However, the environment in which the drilling tools operate is at significant distances below the surface and measurements to manage operation of such equipment are made at these locations. Further, the usefulness of such measurements may be related to the precision or quality of the information derived from such measurements.

Brief Description of the Drawings

Figure 1 shows features of a method of determining properties associated with operating a tool in a borehole of a well, according to various embodiments.

Figure 2 shows an antenna configuration for a multi-component electromagnetic logging tool, according to various embodiments.

Figures 3A-B illustrate two kinds of antenna structures that can be used in a logging tool, according to various embodiments.

Figure 3C shows quadrants for the tilt angles of antenna structures of Figures 3A-B, according to various embodiments.

Figures 3D-E illustrate multiple sets of antennas tilted with respect to the axis of the tool in which they are configured, according to various embodiments.

Figure 4 shows a configuration of tool bin positions and corresponding azimuthal angles, according to various embodiments.

Figure 5 shows a tool with two transmitters tilted at +45 and -45 degrees and central receivers tilted at an angle of 45 degrees with respect to a longitudinal axis, according to various embodiments.

Figure 6 shows an example flow chart of performing a rotating logging tool, according to various embodiments.

Figure 7 A-B shows inversion results using the responses of the antenna configuration for a tool shown in Figure 5 for a particular formation model, in accordance with various embodiments.

Figure 8 A-B shows inversion results using the responses of the antenna configuration for a tool shown in Figure 5 for another formation model, in accordance with various embodiments.

Figure 9 illustrates an example response of a complex voltage referenced to the cross-coupling measurements for the upper transmitter-receiver pair of Figure 5 when drilling in a three-layer isotropic formation, in accordance with various embodiments.

Figure 10 illustrates an example response of a complex voltage referenced to the cross-coupling measurements for the lower transmitter-receiver pair of Figure 5 when drilling in the three-layer isotropic formation of Figure 9, in accordance with various embodiments.

Figure 11 illustrates an example response of a complex voltage referenced to the cross-coupling measurements for the upper transmitter-receiver pair of Figure 5 when drilling in a three-layer anisotropic formation, in accordance with various embodiments.

Figure 12 illustrates an example response of a complex voltage referenced to the cross-coupling measurements for the lower transmitter-receiver pair of Figure 5 when drilling in the three-layer anisotropic formation of Figure 11, in accordance with various embodiments.

Figure 13 illustrates an example a geosignal phase for a three-layer isotropic formation, according to various embodiments.

Figure 14 illustrates an example a geosignal attenuation for the three-layer isotropic formation of Figure 13, according to various embodiments.

Figure 15 illustrates an example a geosignal phase for a three-layer anisotropic formation, according to various embodiments.

Figure 16 illustrates an example a geosignal attenuation for the three-layer anisotropic formation of Figure 15, according to various embodiments.

Figure 17 depicts a block diagram of features of an embodiment of a system to process signals, from a tilted receiver in response to firing multiple antennas independently, to directly determine a coupling matrix, according to

various embodiments.

Figure 18 depicts an embodiment of a system at a drilling site, according to various embodiments.

Detailed Description

The following detailed description refers to the accompanying drawings that show, by way of illustration and not limitation, various embodiments in which the invention may be practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice these and other embodiments. Other embodiments may be utilized, and structural, logical, and electrical changes may be made to these embodiments. The various embodiments are not necessarily mutually exclusive, as some embodiments can be combined with one or more other embodiments to form new embodiments. The following detailed description is, therefore, not to be taken in a limiting sense.

Figure 1 shows features of an embodiment of a method of determining properties associated with operating a tool in a borehole of a well. At 110, voltage signals generated from operating a tool rotating in a borehole of a well are acquired, where the tool includes multiple transmitter antennas and a receiver antenna tilted with respect to the longitudinal axis of the tool. The acquired voltage signals can include voltage signals received at the tilted receiver antenna in response to firing separately the transmitter antennas associated with the tilted receiver antenna. The receiver and transmitter antennas of the tool can have various configurations. For example, two transmitter antennas can be placed essentially at the same location with different orientations. These transmitter antennas can be located on the tool above or below the tilted receiver antenna with respect to the longitudinal axis of the tool. In various embodiments, the tilted receiver antenna can be placed between the two transmitters with the two transmitters having different orientations. In various embodiments, in addition to the tilted receiver antenna, another tilted receiver antenna may be used. The two receiver antennas can placed between two transmitter antennas, where the two transmitter antennas have different orientations. Alternatively, two transmitter antennas can be used disposed between two titled receiver antennas. In each of these configurations, one or more of the transmitter antennas used can be tilted

with respect to the longitudinal axis of the tool.

At 120, the acquired voltage signals are processed with respect to a direction in the rotation of the tool to determine properties associated with a formation in vicinity of the borehole, where the processing includes determining a coupling matrix from the acquired voltage signals. Such voltage signals can be generated from firing one of the transmitters and measuring a response at a tilted receiver with respect to the firing and firing another transmitter and measuring a response at a tilted receiver with respect to the firing of the other transmitter. The term firing is used to visualize transmitting a signal into a formation in the vicinity of the tool in the well. The transmitters are fired independent of one another such that a response a receiver can be correlated to the firing transmitter. This correlation can be realized by a processing unit keeping track of the measurement activities and their timing. The firing can include transmitting pulses from a transmitter such that each pulse is emitted from the transmitter while the other transmitters are in a period during which no pulses are emitted. In various embodiments, current measurements can be used to acquire signals to generate a coupling matrix.

Processing can include directly calculating coupling voltage components for a coupling matrix from the measured responses received in response to the set of transmitter firings. Direct calculation can include multiplication and addition related operations. However, such direct calculations can be conducted without more processing such as associated with solving a set of equations. Since the measured responses are related to electromagnetic propagation in the formation in the vicinity of the tool, one or more inversion operations can be performed to generate formation parameters from the determined coupling matrix. Inversion operations can include a comparison of measurements to predictions of a model such that a value or spatial variation of a physical property can be determined. A conventional inversion operation can include determining a variation of electrical conductivity in a formation, in the vicinity of the borehole that is being operated upon, from measurements of induced electric and magnetic fields.

The tool with its oriented antennas can be configured with an implementation in the borehole of a well as a measurements-while-drilling (MWD) system such as a logging-while-drilling (LWD) system or as a wireline

system. A processing unit and/or a control unit can be configured downhole with the measuring antennas. Alternatively, one or more of a processing unit and a control unit can be configured at the surface of a well with a communication network to acquire information and/or to generate control signals with respect to the antennas of the tool. The communications can use wired or wireless communication mechanism associated with known downhole communication techniques.

In various embodiments, apparatus and processing schemes provide for electromagnetic logging with rotating tilted antenna systems with enhanced direct processing that use the measured signals when the tool is rotating in a borehole. Such processing schemes allow the solution of the coupling voltage matrix. Processing techniques can be based on a rotating LWD or wireline tool equipped with at least two tilted transmitter antennas and one tilted receiver antenna. This configuration along with processing schemes, discussed herein, allows the calculation of anisotropy, as exhibited by a horizontal resistivity R_h and a vertical resistivity R_v, and the relative dip angle at any borehole deviation from the solution of the coupling voltage matrix determined form the measured signals. The relative dip angle is an angle between a planar feature such as a formation and a horizontal plane.

In various embodiments, apparatus and processing schemes, as discussed herein, can be used for geosteering operations. Geosteering is an intentional control to adjust drilling direction. The control can be based on downhole logging measurements to increase the borehole's exposure to a hydrocarbon-bearing formation (the "payzone"). Such geosteering can be used to maintain a wellbore within a region that provides a material that is a source of economic value. A geosignal is a signal or representation that can be used for geosteering. Geosignals are indicative of the direction of drilling tools downhole as well as capable of detecting boundaries. Capabilities of geosignals are useful in geosteering to optimize well placement for maximum oil recovery. Apparatus and processing schemes, as discussed herein, allow for the generation of a geosignal. A geosignal may be based one or more properties of earth formations as a function of distance from a reference point. The geosignals defined herein have a variety of applications. Geosignals also provide azimuthal orientation information of

rotary tools. In addition, the geosignal can be used for the calculation of distance to bed boundaries. Processing techniques for the geosignal can be based on a rotating LWD or wireline tool equipped with at least two tilted transmitter antennas and one tilted receiver antenna. A configuration of one tilted transmitter antenna and one tilted receiver antenna can also be implemented to generate a geosignal.

Figure 2 shows an embodiment of an antenna configuration for a multi-component electromagnetic logging tool. The magnetic field $\boldsymbol{H}$ in the receiver coils can be represented in terms of the magnetic moments $\boldsymbol{M}$ at the transmitters and a coupling matrix C as:

$$\boldsymbol{H=CM} \tag{1}$$

Equation (1) can be expressed as:

$$\begin{bmatrix} H_x \\ H_y \\ H_z \end{bmatrix} = \begin{bmatrix} C_{xx} & C_{xy} & C_{xz} \\ C_{yx} & C_{yy} & C_{yz} \\ C_{zx} & C_{zy} & C_{zz} \end{bmatrix} \begin{bmatrix} M_x \\ M_y \\ M_z \end{bmatrix} \tag{2}$$

where M_X, M_Y, and M_Z are the magnetic moments of the transmitted signal emitted by transmitters T_X, T_Y, and T_Z, respectively. H_X, H_Y, and H_Z are the magnetic fields, which are proportional to the received signal at the receiver antennas R_X, R_Y, and R_Z, respectively. For the antenna configuration of Figure 2, nine absolute or differential measurements can be obtained when each antenna is fired and a signal is measured at each of the three receivers, respectively. These nine measurements enable the determination of a complete coupling matrix C. The components, C_{IJ}, can be defined as $C_{IJ} = a_{IJ} \cdot V_I^J$, where I is the index of receiver R_X, R_Y, and R_Z, J is the index of receiver T_X, T_Y, and T_Z, a_{IJ} is a constant coefficient determined by the tool design, and V_I^J is a complex value representing the signal amplitude and phase shift measured by receiver I in response to the firing of transmitter J. In various embodiments, current measurements can be used to acquire signals to generate a coupling matrix.

Figures 3A-B show a titled transmitter antenna and a tilted receiver antenna for a measuring tool. Such antennas can be equipped in a rotating LWD or wireline tool. While firing the transmitter antenna, the signal measured at the

titled receiver of Figure 3 can be expressed in terms of the signal voltage V_R^T, where T represents the firing transmitter antenna and R represents the receiving antenna. With both transmitter and receiver coils are oriented at the same azimuth angle β, the measured signal at the titled receiver is expressed as,

$$V_R^T(\beta) = \begin{bmatrix} \sin\theta_t \cos\beta \\ \sin\theta_t \sin\beta \\ \cos\theta_t \end{bmatrix} \begin{bmatrix} V_x^x & V_y^x & V_z^x \\ V_x^y & V_y^y & V_z^y \\ V_x^z & V_y^z & V_z^z \end{bmatrix} \begin{bmatrix} \sin\theta_r \cos\beta \\ \sin\theta_r \sin\beta \\ \cos\theta_r \end{bmatrix}, \quad (3)$$

where θ_t is the tilt angle of the transmitter antenna relative to the z-axis (z-axis 301-A in Figure 3A and z-axis 301-B in Figure 3B) and θ_r is the tilt angle of the receiver related to the z-axis direction. Herein, θ_t and θ_r only range between -90 degree and 90 degree shown in Figures 3A-B. Based on equation (3), the measured signal can be also expressed as

$$V_R^T(\beta) = C_{xx}\cos^2\beta + C_{xy}\cos\beta\sin\beta + C_{xz}\cos\beta + C_{yx}\cos\beta\sin\beta + C_{yy}\sin^2\beta + C_{yz}\sin\beta + C_{zx}\cos\beta + C_{zy}\sin\beta + C_{zz} \quad (4)$$

where

$$C_{xx} = V_x^x \sin\theta_t \sin\theta_r \;;\; C_{xy} = V_y^x \sin\theta_t \sin\theta_r \;;\; C_{xz} = V_z^x \sin\theta_t \cos\theta_r$$
$$C_{yx} = V_x^y \sin\theta_t \sin\theta_r \;;\; C_{yy} = V_y^y \sin\theta_t \sin\theta_r \;;\; C_{yz} = V_z^y \sin\theta_t \cos\theta_r .$$
$$C_{zx} = V_x^z \cos\theta_t \sin\theta_r \;;\; C_{zy} = V_y^z \cos\theta_t \sin\theta_r \;;\; C_{zz} = V_z^z \cos\theta_t \cos\theta_r$$

Solving each component (V_I^J) of the coupling complex voltage matrix defined in equation (3) allows for the performance of one or more accurate inversion process that can generate formation properties for the well in which the tool is operating.

Figures 3A-B illustrate two kinds of antenna structures that can be used to achieve direct solutions of coupling complex voltage matrix according to embodiments of processes discussed herein. The first type of structure, shown in Figure 3A, includes two tilted transmitters placed at the same location with different orientations and a tilted receiver at a distance d from the transmitters. The tilt of these antennas is with respect to longitudinal axis 301-A. The second type of structure, shown in Figure 3B, has a configuration with a tilted receiver placed at the center of two tilted transmitters with different orientations. To directly solve the coupling complex voltage matrix of either configuration in

Figures 3A-B, two criteria are used. The first criterion is that the orientation of the receiver antenna cannot have a tilt angle of zero degrees and the orientation of the two transmitters cannot both be zero at the same time. The other criterion is that the orientations of the two transmitters are in adjacent quadrants. Figure 3C shows an example of the quadrants with respect to tilt relative to the z-axis. In an embodiment, the tilt angles can be limited in either the first quadrant or the forth quadrant shown in Figure 3C. Consequently, if the tilt angle of one transmitter, θ_{t1} of T_1, for example, of Figures 3A-B is in the first quadrant, the orientation of the other transmitter, θ_{t2} of T_2, for example, is in the forth quadrant. For simplicity, the orientation of one transmitter to the other transmitter is reversed in Figures 3A-B, that is, θ_{t1} equals $-\theta_{t2}$. With these parameters for orientation of tilted receiver and transmitters and using either one of the structures shown in Figures 3A-B, each component of the coupling complex voltage matrix can be directly derived from following equations (5a) to (5h).

$$V_z^z = \frac{1}{2N\cos\theta_{t1}\cos\theta_r}\left[\sum_{i=1}^{N} V_R^{T_1}\left(\frac{\beta_m}{2}+(i-1)\times\beta_i\right)+\sum_{i=1}^{N} V_R^{T_2}\left(\frac{\beta_m}{2}+(i-1)\times\beta_i\right)\right] \quad (5a)$$

$$V_x^x = \frac{\left[\cos^2\left(\frac{\beta_m}{2}\right)-\sin^2\left(\frac{\beta_m}{2}\right)\right]^{-1}}{2\sin\theta_{t1}\sin\theta_r}\left\{\frac{1}{4}\left[V_R^{T_1}(\frac{\beta_m}{2})+V_R^{T_1}(\frac{\beta_m}{2}+\pi)+V_R^{T_1}(2\pi-\frac{\beta_m}{2})\right.\right.$$
$$\left.+V_R^{T_1}(\pi-\frac{\beta_m}{2})-V_R^{T_2}(\frac{\beta_m}{2})-V_R^{T_2}(\frac{\beta_m}{2}+\pi)-V_R^{T_2}(2\pi-\frac{\beta_m}{2})-V_R^{T_2}(\pi-\frac{\beta_m}{2})\right]-$$
$$\frac{\sin^2\left(\frac{\beta_m}{2}\right)}{2}\left[V_R^{T_1}(\frac{\beta_m}{2})+V_R^{T_1}(\frac{\beta_m}{2}+\pi)+\right.$$
$$\left.\left.V_R^{T_1}(\frac{\beta_m}{2}+\frac{\pi}{2})+V_R^{T_1}(\frac{\beta_m}{2}+\frac{3\pi}{2})-V_R^{T_2}(\frac{\beta_m}{2})-V_R^{T_2}(\frac{\beta_m}{2}+\pi)-V_R^{T_2}(\frac{\beta_m}{2}+\frac{\pi}{2})-V_R^{T_2}(\frac{\beta_m}{2}+\frac{3\pi}{2})\right]\right\} \quad (5b)$$

$$V_y^y = -V_x^x + \frac{1}{2\sin\theta_{t1}\sin\theta_r} \times \left[\frac{V_R^{T_1}(\frac{\beta_m}{2}) + V_R^{T_1}(\frac{\beta_m}{2}+\pi) + V_R^{T_1}(\frac{\beta_m}{2}+\frac{\pi}{2}) + V_R^{T_1}(\frac{\beta_m}{2}+\frac{3\pi}{2})}{2} - \frac{V_R^{T_2}(\frac{\beta_m}{2}) + V_R^{T_2}(\frac{\beta_m}{2}+\pi) + V_R^{T_2}(\frac{\beta_m}{2}+\frac{\pi}{2}) + V_R^{T_2}(\frac{\beta_m}{2}+\frac{3\pi}{2})}{2} \right] \quad (5c)$$

$$V_x^y = V_y^x = \frac{V_x^y + V_y^x}{2} = \frac{\left[V_R^{T_1}(\frac{\beta_m}{2}) + V_R^{T_1}(\frac{\beta_m}{2}+\pi) - V_R^{T_2}(\frac{\beta_m}{2}) - V_R^{T_2}(\frac{\beta_m}{2}+\pi) \right]}{-2\sin\theta_{t1}\sin\theta_r} + 2V_x^x\cos^2(\frac{\beta_m}{2}) + 2V_y^y\sin^2(\frac{\beta_m}{2})}{-4\cos(\frac{\beta_m}{2})\sin(\frac{\beta_m}{2})} \quad (5d)$$

$$V_z^x = \frac{V_R^{T_1}(\frac{\beta_m}{2}) + V_R^{T_1}(2\pi - \frac{\beta_m}{2}) + V_R^{T_2}(\frac{\beta_m}{2}+\pi) + V_R^{T_2}(\pi - \frac{\beta_m}{2})}{4\sin\theta_{t1}\cos\theta_r\cos(\frac{\beta_m}{2})} - \frac{V_z^z\cot\theta_{t1}}{\cos(\frac{\beta_m}{2})} \quad (5e)$$

$$V_z^y = \frac{V_R^{T_1}(\frac{\beta_m}{2}+\frac{\pi}{2}) + V_R^{T_1}(\frac{\pi}{2} - \frac{\beta_m}{2}) + V_R^{T_2}(\frac{\beta_m}{2}+\frac{3\pi}{2}) + V_R^{T_2}(\frac{3\pi}{2} - \frac{\beta_m}{2})}{4\sin\theta_{t1}\cos\theta_r\cos(\frac{\beta_m}{2})} - \frac{V_z^z\cot\theta_{t1}}{\cos(\frac{\beta_m}{2})} \quad (5f)$$

$$V_x^z = \frac{V_R^{T_1}(\frac{\beta_m}{2}) + V_R^{T_1}(2\pi - \frac{\beta_m}{2}) + V_R^{T_2}(\frac{\beta_m}{2}) + V_R^{T_2}(2\pi - \frac{\beta_m}{2})}{4\cos\theta_{t1}\sin\theta_r\cos(\frac{\beta_m}{2})} - \frac{V_z^z\cot\theta_r}{\cos(\frac{\beta_m}{2})} \quad (5g)$$

$$V_y^z = \frac{V_R^{T_1}(\frac{\beta_m}{2}+\frac{\pi}{2}) + V_R^{T_1}(\frac{\pi}{2} - \frac{\beta_m}{2}) + V_R^{T_2}(\frac{\beta_m}{2}+\frac{\pi}{2}) + V_R^{T_2}(\frac{\pi}{2} - \frac{\beta_m}{2})}{4\cos\theta_{t1}\sin\theta_r\cos(\frac{\beta_m}{2})} - \frac{V_z^z\cot\theta_r}{\cos(\frac{\beta_m}{2})} \quad (5h)$$

where $V_R^{T_1}$ and $V_R^{T_2}$ are measured voltages at the receiver (R) when emitting

transmitter T_1 and transmitter T_2, respectively, are independently firing.

While the tool is rotating, the value of $V_R^{T_1}$ or $V_R^{T_2}$ varies with respect to azimuth angle β defined in equation (3). The rotation of the tool can be partitioned into N segments, called bins, in which completion of the N bins is one complete rotation of the tool, N $\geq$2, where N is the total number of bins. Each bin has an associated azimuthal angle β. With the tool rotation partitioned into equal amounts of angular rotation, each bin has an equal angle of rotation, β_m. As shown in Figure 4, β_m is an evenly-divided azimuthal angle given by $\beta_m = 2\pi/N$, where m demotes that the azimuthal angle considered is for the mth bin. Thus, equations 5(a)-5(h) provide the components of the coupling complex voltage matrix from measured responses in a selected bin, which corresponds to a particular direction as shown in Figure 4. In various applications, N can be equal to 32. However, N can be set to other values.

In various embodiments, sets of transmitting and receiving antennas can be arranged in a tilted transmitter-receiver (Tx-Rx) antenna system to provide responses from probing formations in a well hole to be used to provide a coupling complex voltage matrix that can be used to determine properties associated with the formations. Figure 3D illustrates an embodiment of multiple sets of antennas tilted with respect to axis 301-D. One set includes two tilted transmitters, T_1 and T_2, placed at the same location with different orientations and a tilted receiver, R_1, at a distance d_1 from the transmitters T_1 and T_2. Another set includes two tilted transmitters, T_3 and T_4, placed at the same location with different orientations and a tilted receiver, R_2, at a distance d_1 from the transmitters T_3 and T_4. In this configuration, two matrices of coupling complex voltages can be obtained with one matrix related to the configuration relative to distance d_1 and the other matrix utilized with regards to structures with a distance d_2 taking into account upper transmitters, T_1 and T_2, with lower receiver R_2 and lower transmitters T_3 and T_4 with upper receiver R_1.

Figure 3E illustrates an embodiment of multiple sets of antennas tilted with respect to axis 301-E. One set includes one tilted transmitter, T_1, placed above two tilted receivers, R_1 and R_2, at the same location with different orientations at a distance d_1 from the transmitter T_1. Another set includes one

tilted transmitter, T_2, placed below two tilted receivers, R_3 and R_4, at the same location with different orientations at a distance d_1 from the transmitter T_2. In this configuration, two matrices of coupling complex voltages can be obtained with one matrix related to the configuration relative to distance d_1 and the other matrix utilized with regards to structures with a distance d_2 taking into account upper transmitter, T_1, with lower receivers R_3 and R_4 and lower transmitter T_2 with upper receivers R_1 and R_2. Other configurations of transmitter and receiver antennas can be used to provide response signals for processing to determine properties associated with formations around a well hole in accordance with various embodiments discussed herein.

With the orientations of the antennas fixed by the criteria discussed above and with θ_{t1} equals $-\theta_{t2}$, equations 5(a) – 5(h) can be further simplified by choosing a particular tilt angle. Figure 5 shows an embodiment of a tool with two transmitters tilted at +45 and -45 degrees and central receivers tilted at an angle of 45 degrees with respect to longitudinal axis 501. This configuration provides a perpendicularly tilted transmitter-receiver (Tx-Rx) antenna system. In this configuration, two matrices of coupling complex voltages can be obtained. As shown in Figure 5, one voltage matrix is related to the configuration of antenna structures with a distance d_1 between a signal transmitter antenna and a signal receiver antenna, in which acquired responses include the signals of $V_{R_{up}}^{T_{up}}$ and $V_{R_{dn}}^{T_{dn}}$ with respect to T_{up}, R_{up}, T_{dn}, and R_{dn} shown in Figure 5. The other voltage matrix is utilized with regards to structures with a distance d_2 between a signal transmitter and a signal receiver, which involves the signals of $V_{R_{dn}}^{T_{up}}$ and $V_{R_{up}}^{T_{dn}}$ with respect to T_{up}, R_{up}, T_{dn}, and R_{dn} shown in Figure 5. Then, each component of either coupling complex voltage matrix can be directly processed as follows.

$$V_z^z = \frac{1}{N}\sum_{i=1}^{N} V_R^U\left(\frac{\beta_m}{2}+(i-1)\times\beta_i\right)+\frac{1}{N}\sum_{i=1}^{N} V_R^L\left(\frac{\beta_m}{2}+(i-1)\times\beta_i\right) \qquad (6a)$$

$$V_x^x = \left\{\frac{1}{4}\times\left[V_R^U(\frac{\beta_m}{2})+V_R^U(\frac{\beta_m}{2}+\pi)+V_R^U(2\pi-\frac{\beta_m}{2})+V_R^U(\pi-\frac{\beta_m}{2})-V_R^L(\frac{\beta_m}{2})-V_R^L(\frac{\beta_m}{2}+\pi)\right.\right.$$
$$\left.-V_R^L(2\pi-\frac{\beta_m}{2})-V_R^L(\pi-\frac{\beta_m}{2})\right]-\frac{\sin^2(\frac{\beta_m}{2})}{2}\times\left[V_R^U(\frac{\beta_m}{2})+V_R^U(\frac{\beta_m}{2}+\pi)+V_R^U(\frac{\beta_m}{2}+\frac{\pi}{2})+V_R^U(\frac{\beta_m}{2}+\frac{3\pi}{2})\right.$$
$$\left.\left.-V_R^L(\frac{\beta_m}{2})-V_R^L(\frac{\beta_m}{2}+\pi)-V_R^L(\frac{\beta_m}{2}+\frac{\pi}{2})-V_R^L(\frac{\beta_m}{2}+\frac{3\pi}{2})\right]\right\}\times\left[\sin^2(\frac{\beta_m}{2})-\cos^2(\frac{\beta_m}{2})\right]^{-1} \quad (6b)$$

$$V_y^y = -V_x^x - \frac{V_R^U(\frac{\beta_m}{2})+V_R^U(\frac{\beta_m}{2}+\pi)+V_R^U(\frac{\beta_m}{2}+\frac{\pi}{2})+V_R^U(\frac{\beta_m}{2}+\frac{3\pi}{2})}{2}+$$
$$\frac{V_R^L(\frac{\beta_m}{2})+V_R^L(\frac{\beta_m}{2}+\pi)+V_R^L(\frac{\beta_m}{2}+\frac{\pi}{2})+V_R^L(\frac{\beta_m}{2}+\frac{3\pi}{2})}{2} \quad (6c)$$

$$V_x^y = V_y^x = \frac{V_x^y+V_y^x}{2}$$
$$= \frac{\left[V_R^U(\frac{\beta_m}{2})+V_R^U(\frac{\beta_m}{2}+\pi)-V_R^L(\frac{\beta_m}{2})-V_R^L(\frac{\beta_m}{2}+\pi)\right]+2V_x^x\cos^2(\frac{\beta_m}{2})+2V_y^y\sin^2(\frac{\beta_m}{2})}{-4\cos(\frac{\beta_m}{2})\sin(\frac{\beta_m}{2})} \quad (6d)$$

$$V_z^x = \frac{V_R^U(\frac{\beta_m}{2})+V_R^U(2\pi-\frac{\beta_m}{2})+V_R^L(\frac{\beta_m}{2}+\pi)+V_R^L(\pi-\frac{\beta_m}{2})}{-2\cos(\frac{\beta_m}{2})}+\frac{V_z^z}{\cos(\frac{\beta_m}{2})} \quad (6e)$$

$$V_z^y = \frac{V_R^U(\frac{\beta_m}{2}+\frac{\pi}{2})+V_R^U(\frac{\pi}{2}-\frac{\beta_m}{2})+V_R^L(\frac{\beta_m}{2}+\frac{3\pi}{2})+V_R^L(\frac{3\pi}{2}-\frac{\beta_m}{2})}{-2\cos(\frac{\beta_m}{2})}+\frac{V_z^z}{\cos(\frac{\beta_m}{2})} \quad (6f)$$

$$V_x^z = \frac{V_R^U(\frac{\beta_m}{2})+V_R^U(2\pi-\frac{\beta_m}{2})+V_R^L(\frac{\beta_m}{2})+V_R^L(2\pi-\frac{\beta_m}{2})}{2\cos(\frac{\beta_m}{2})}-\frac{V_z^z}{\cos(\frac{\beta_m}{2})} \quad (6g)$$

$$V_y^z = \frac{V_R^U(\frac{\beta_m}{2}+\frac{\pi}{2}) + V_R^U(\frac{\pi}{2}-\frac{\beta_m}{2}) + V_R^L(\frac{\beta_m}{2}+\frac{\pi}{2}) + V_R^L(\frac{\pi}{2}-\frac{\beta_m}{2})}{2\cos(\frac{\beta_m}{2})} - \frac{V_z^z}{\cos(\frac{\beta_m}{2})} \quad (6h)$$

where V_R^U is a measured voltage at receivers (R_{up} or R_{dn}) when the upper transmitter (T_{up}) is used and V_R^L is measured voltage at receivers (R_{up} or R_{dn}) when the lower transmitter (T_{dn}) is used. The nomenclature V_R^U ( ) means the measured voltage V_R^U at the bin corresponding to the azimuthal angle listed within ( ). For instance, V_R^U ($\beta_m/2$) means the measured voltage V_R^U at the selected bin, which is bin 1 shown in Figure 4 if the azimuthal angle of high side is defined as zero, and V_R^U ($\beta_m/2 + \pi/2$) means the measured voltage V_R^U at the bin that is a positive 90 degrees in the rotation from the selected bin. In addition, V_R^U ($\beta_m/2 + (i\text{-}1)\,\beta_i$) means the measured voltage V_R^U at the bin that is (i-1) bins in the rotation from the selected bin.

According to the principle of reciprocity, one should expect that one antenna may be applied as a transmitter in one implementation and as a receiver at another. The configurations of transmitters-receivers antenna system disclosed herein can be interchangeable, i.e., transmitters can be used as receivers and receivers can be used as transmitters.

Once the coupling voltages matrix is obtained using the above described processing, formation parameters can be obtained using standard inversion techniques, such as a least squares method. A flow chart of an embodiment of a method implementing the configuration of tilted antennas as shown in Figure 5 is presented in Figure 6. At 610, initial upper and lower transmitters are selected for firing. At 620, the selected transmitters are fired separately and receiver responses are measured. At 630, the measured signals at the receivers responsive to the firing of the upper and lower transmitters are processed. At 640, the tool position and orientation are collected. The tool position is correlated to a specific bin for the measured signals. The tool may include a sensor or other mechanism to determine tool position and tool orientation including with respect to azimuthal angle. For a bin, nine coupling voltage components are calculated in accordance with equations 5(a)-5(h). At 650, from the nine coupling voltage components,

inversion operations can be performed to determine formation properties. These formation properties may be determined essentially in real-time or as a post-process operation. At 660, from the nine coupling voltage components, a geosignal may be determined. The geosignal may used in a geosteering operation in the well. The geosignal determination and subsequent geo steering may be performed essentially in real-time or as a post-process operation. At 670, a determination is made as to whether additional measurements are to be taken. These additional measurements may be conducted for one or more other bins.

Several modeling cases were evaluated with respect to the processes described above under a wide range of dip angle, R_h values, and R_v values. Figures 7A-B shows inversion results using the responses of the antenna configuration for a tool shown in Figure 5 for a particular formation model. The formation model includes a horizontal resistivity R_h of 0.7 $\Omega \cdot m$ and a vertical resistivity R_v of 5.0 $\Omega \cdot m$ at arbitrary relative dip angle from 0 degrees to 90. Curve 707 in Figure 7A shows the inversion results for R_v from the tool and curve 709 shows the inversion results for R_h from the tool. Figure 7B shows the dip angle from the inversion results that matches the dip angle from the model.

Figure 8 shows inversion results using the responses of the antenna configuration for a tool shown in Figure 5 for another formation model. This formation model includes a horizontal resistivity R_h of 2.5 $\Omega \cdot m$ and a vertical resistivity R_v of 5.0 $\Omega \cdot m$ at arbitrary relative dip angle from 0 degrees to 90 degrees. Curve 807 in Figure 8A shows the inversion results for R_v from the tool and curve 809 shows the inversion results for R_h from the tool. Figure 8B shows the dip angle from the inversion results that matches the dip angle from the model. These inversion results for bin 1 shown in Figures 7A-B and 8A-B produce good solutions and compare well with modeled data, which demonstrates the robustness of the techniques of the various embodiments at all hole deviations.

In various embodiments, geosignal responses can be determined using tools equipped with tilted transmitter and tilted receiver structures as discussed herein. The determined geosignal responses can be used for geosteering applications. Such geosteering applications can be conducted with, but are not limited to, rotating LWD tools equipped with tilted transmitter and tilted receiver structures. Geosignal responses can be calculated by processing the measured

signal at the receivers. For a rotating tilted transmitter and tilted receiver tool with azimuthal angle β, a complex voltage $V_{CZ}(\beta)$ referenced to the cross-coupling measurements (for example, ZX and XZ measurements with the z-axis oriented as in Figures 1-5 and x-axis orthogonal to the z-axis as in Figure 1) is defined as:

$$V_{CZ}(\beta)=\frac{1}{4\sqrt{2}}\left[V_R^T(\beta-\frac{\pi}{4})-V_R^T(\beta+\frac{3\pi}{4})+V_R^T(\beta+\frac{\pi}{4})-V_R^T(\beta+\frac{5\pi}{4})\right] \quad (7)$$

Figure 9 illustrates an example response of $V_{CZ}(\beta)$ for the upper transmitter-receiver pair (T_{up} and R_{up}) of Figure 5 when drilling in a three-layer isotropic formation. Transmitter T_{up} is fired and the voltage at R_{up} is measured for the azimuthal direction defined by bin 1 of Figure 4. $V_{CZ}(\beta)$ has a real part 917 and an imaginary part 919, where both parts show significant changes at boundaries 901 and 903. Figure 10 illustrates an example response of $V_{CZ}(\beta)$ for the lower transmitter-receiver pair (T_{dn} and R_{dn}) of Figure 5 when drilling in the three-layer isotropic formation. Transmitter T_{dn} is fired and the voltage at R_{dn} is measured for the azimuthal direction defined by bin 1 of Figure 4. $V_{CZ}(\beta)$ has a real part 1017 and an imaginary part 1019, where both parts show changes at boundaries 901 and 903. The drilling for the examples of Figures 9 and 10 is at a relative dip angle of 85 degrees. The first layer has a resistivity of 1 ohm-m, the middle layer has a resistivity of 10 ohm-m, and the last layer has a resistivity of 1 ohm-m.

Figure 11 illustrates an example response of $V_{CZ}(\beta)$ for the upper transmitter-receiver pair (T_{up} and R_{up}) of Figure 5 when drilling in a three-layer anisotropic formation. Transmitter T_{up} is fired and the voltage at R_{up} is measured for the azimuthal direction defined by bin 1 of Figure 4. $V_{CZ}(\beta)$ has a real part 1117 and an imaginary part 1119, where both parts show significant changes at boundaries 1101 and 1103. Figure 10 illustrates an example response of $V_{CZ}(\beta)$ for the lower transmitter-receiver pair (T_{dn} and R_{dn}) of Figure 5 when drilling in the three-layer anisotropic formation of Figure 11. Transmitter T_{dn} is fired and the voltage at R_{dn} is measured for the azimuthal direction defined by bin 1 of Figure 4.

$V_{CZ}(\beta)$ has a real part 1217 and an imaginary part 1219, where both parts show changes at boundaries 1101 and 1103. The drilling for the examples of Figures 11 and 12 is also at a relative dip angle of 85 degrees. The first layer of this anisotropic formation has a horizontal resistivity R_h of 1 ohm-m and a vertical resistivity R_v of 4 ohm-m, the middle layer has a horizontal resistivity R_h of 10 ohm-m and a vertical resistivity R_v of 50 ohm-m, and the last layer has a horizontal resistivity R_h of 1 ohm-m and a vertical resistivity R_v of 4 ohm-m.

From Figures 9 to 12, it can be concluded that a perpendicularly tilted transmitter-receiver antenna system is capable of providing geosteering information and detecting boundary positions. If both tilt transmitter and tilt receiver are oriented in different adjacent quadrants (depicted in Figure 3C), the measured signals at the receiver will be proportional to the subtraction of coupling voltage components V_x^z and V_z^x such that the measured signals are only sensitive to boundary effects. These measured signals are available to present geosignal responses, according to various embodiments. However, if tilt transmitter and tilt receiver are oriented in the same quadrant or diagonal quadrants, such as 1^{st}-3^{rd} quadrants or 2^{nd}-4^{th} quadrants, the measured signals effectively in part contain a summation effect of coupling voltage components V_x^z and V_z^x. Such summation effect is sensitive to intertwined effects among anisotropy, relative dip angle, and boundary. As a result, the corresponding geosignal responses with tilt transmitter and tilt receiver oriented in the same quadrant or diagonal quadrants do not provide responses that are as good for geosteering as those provided with both tilt transmitter and tilt receiver are oriented in different adjacent quadrants.

In various embodiments, an antenna system equipped with the upper transmitter and central receivers of Figure 5, in which both tilt transmitter and tilt receiver are oriented in different adjacent quadrants, can be used in geosteering applications. A geosignal response can be obtained as:

$$V_{Geo}(\beta) = \frac{V_R^T(\beta)}{V_R^T(\beta+\pi)}, \qquad (8)$$

which is the measured signal V_R^T in a current bin, which is one bin direction of the N bin directions as shown in Figure 4, divided by the measured signal V_R^T in the bin 180 degrees from the current bin. The geosignal responses can be expressed

in terms of geosignal phase ϕ_{Geo} and geosignal attenuation A_{Geo} as follows:

$$\phi_{Geo}(\beta) = phase\{V_R^T(\beta)\} - phase\{V_R^T(\beta+\pi)\} \quad (9a)$$

$$A_{Geo}(\beta) = \log|V_R^T(\beta)| - \log|V_R^T(\beta+\pi)| \quad (9b)$$

Figure 13 illustrates an example a geosignal phase for a three-layer isotropic formation. The geosignal phase ϕ_{Geo} of equation (9a) shown in Figure 13 is for a perpendicular Tx-Rx pair of Figure 5 in the direction of bin one of Figure 4. Figure 14 illustrates an example a geosignal attenuation for the three-layer isotropic formation of Figure 13. The geosignal attenuation A_{Geo} of equation (9b) shown in Figure 14 is for a perpendicular Tx-Rx pair of Figure 5 in the direction of bin one of Figure 4. Figures 13 and 14 are geosignals generated from operating the tool of Figure 5 with a transmitter-to-receiver spacing of 32 inch and frequency of 500 kHz at a relative dip angle of 85 degrees. The first layer of this isotropic formation has a resistivity of 1 ohm-m, the middle layer has a resistivity of 10 ohm-m, and the last layer has a resistivity of 1 ohm-m. These geosignals calculated from the measured voltage signal V_R^T show the detection of boundaries 1301 and 1303 as a function of depth.

Figure 15 illustrates an example a geosignal phase for a three-layer anisotropic formation. The geosignal phase ϕ_{Geo} of equation (9a) shown in Figure 15 is for a perpendicular Tx-Rx pair of Figure 5 in the direction of bin one of Figure 4. Figure 16 illustrates an example a geosignal attenuation for the three-layer anisotropic formation of Figure 15. The geosignal attenuation A_{Geo} of equation (9b) shown in Figure 16 is for a perpendicular Tx-Rx pair of Figure 5 in the direction of bin one of Figure 4. Figures 15 and 16 are geosignals generated from operating the tool of Figure 5 also with a transmitter-to-receiver spacing of 32 inch and frequency of 500 kHz at a relative dip angle of 85 degrees. The first layer of this anisotropic formation has a horizontal resistivity R_h of 1 ohm-m and a vertical resistivity R_v of 4 ohm-m, the middle layer has a horizontal resistivity R_h of 10 ohm-m and a vertical resistivity R_v of 50 ohm-m, and the last layer has a horizontal resistivity R_h of 1 ohm-m and a vertical resistivity R_v of 4 ohm-m. These geosignals calculated from the measured voltage signal V_R^T show the detection of boundaries 1501 and 1503 as a function of depth.

In various embodiments, other geosignal responses V_{Geo}^{ZX} and V_{Geo}^{XZ} can be defined that are applicable to drilling operations. Two geosignal responses based on the antenna structure in Figure 5 are defined as:

$$V_{Geo}^{ZX}(\beta) \equiv \frac{V_R^U(\beta)+V_R^L(\beta+\pi)}{\frac{1}{N}\sum_{i=1}^{N}\left[V_R^U\left(\frac{\beta_m}{2}+(i-1)\times\beta_i\right)+V_R^L\left(\frac{\beta_m}{2}+(i-1)\times\beta_i\right)\right]} \quad (10a)$$

$$V_{Geo}^{XZ}(\beta) \equiv \frac{V_R^U(\beta+\pi)+V_R^L(\beta+\pi)}{\frac{1}{N}\sum_{i=1}^{N}\left[V_R^U\left(\frac{\beta_m}{2}+(i-1)\times\beta_i\right)+V_R^L\left(\frac{\beta_m}{2}+(i-1)\times\beta_i\right)\right]}, \quad (10b)$$

where V_{Geo}^{ZX} refers to the signals involved with ZX measurements and V_{Geo}^{XZ} refers to the signals involved with XZ measurements. Both of geosignals are suitable for geosteering operations. In addition, for different antenna structures, the azimuthal angle β of the numerator in equations (10a) and (10b) may plus or minus 180 degrees from the selected bin.

In various embodiments, several processing schemes employ the features of rotating electromagnetic (EM) logging tools. A coupling voltage matrix can be solved directly from the processing of responses of the rotating tool. Furthermore, using the solved coupling voltage matrix, formation parameters can be calculated. These parameters can include formation anisotropy, R_h and R_v, and the relative dip angle at any borehole deviation. In addition, geosignal responses are defined that can be generated from the responses of the rotating tool. These geosignals can be used for geosteering and for calculating the distance to bed boundary (DTBB) using standard inversion techniques. Processing measured voltages as discussed herein allows for the solution of a coupling voltage matrix from which formation parameters such as anisotropy, R_h and R_v, and the relative dip angle can be derived. Unlike conventional processes, these formation parameters can be determined at any borehole deviation. In various embodiments, for deep water situations, processing measured signals, as taught herein, can be used to calculate structure dip and anisotropy in vertical as well as deviated hole, providing structure dip in LWD.

Various components of a measurement tool having a processing unit that determines a complete coupling matrix from direct measurements using tilted

transmitter and receiver antennas, as described herein or in a similar manner, can be realized in hardware implementations, software implementations, and combinations of hardware and software implementations. These implementations may include a machine-readable medium having machine-executable instructions, such as a computer-readable medium having computer-executable instructions, for operating the system to acquire voltage signals generated from operating a tool rotating in a borehole, where the tool includes multiple transmitter antennas and a receiver antenna tilted with respect to the longitudinal axis of the tool and the acquired voltage signals are measured at the tilted receiver antenna in response to firing separately the multiple transmitter antennas associated with the tilted receiver antenna, and to process the acquired voltage signals with respect to a direction in the rotation of the tool to determine properties associated with a formation in vicinity of the borehole, including determining a coupling matrix directly from the acquired voltage signals. The machine-readable medium can also store parameters used in execution of the instructions and can also store results from execution of the instructions. The machine-readable medium can include instructions to generate geosignals from the acquired voltage signals. The machine-readable medium can also include instructions to conduct geosteering based on the geosignals generated from the acquired voltage signals. In various embodiments, current measurements can be used to acquire signals to generate a coupling matrix. The form of machine-readable medium is not limited to any one type of machine-readable medium, but can be any machine-readable medium. For example, machine-readable medium can include a data storage medium that can be implemented in a housing disposed in a collar of a drill string or in a wireline configuration and/or in a system control center.

Figure 17 depicts a block diagram of features of an embodiment of a system 1700 having a processing unit 1705, one or more tilted receiver antennas 1710, and multiple transmitter antennas 1715. Processing unit 1705 is configured to process signals received at one or more tilted receiver antennas 1710 in response to firing multiple transmitter antennas 1715 independently to directly determine a coupling matrix relative to propagation of electromagnetic signals in a formation in the vicinity of a well hole due to the firing of multiple transmitter antennas 1715. Processing unit 1705 can process signals acquired from one or

more tilted receiver antennas 1710 based on the direction relative to rotation of the tool on which one or more tilted receiver antennas 1710 and multiple transmitter antennas 1715 are mounted. Processing unit 1705 can perform processing identical to or similar to the processing schemes discussed with respect to various embodiments herein.

System 1700 can also include a controller 1702, a memory 1725, an electronic apparatus 1735, and a communications unit 1755. Controller 1702, memory 1725, and communications unit 1755 can be arranged to operate one or more tilted receiver antennas 1710 and multiple transmitter antennas 1715 with acquired voltage signals provided to processing unit 105 for the determination of coupling matrices, formation properties, geosignals, and geosteering operations. Processing unit 105 can be located on the surface to a well hole. Processing unit 105 can be located downhole. Processing unit can be integrated with one or more of controller 1702, memory 1725, and communications unit 1755. Processing unit 1705 can be realized to include processing schemes in accordance processing and measurement tools described herein. Communications unit 1755 can include downhole communications in a drilling operation. Such downhole communications can include a telemetry system.

System 1700 can also include a bus 1707, where bus 1707 provides electrical conductivity among the components of system 1700. Bus 1707 can include an address bus, a data bus, and a control bus, each independently configured. Bus 1707 can also use common conductive lines for providing one or more of address, data, or control, the use of which is regulated by controller 1702. Bus 1707 can be configured such that the components of system 1700 are distributed. Such distribution can be arranged between downhole components such as one or more tilted receiver antennas 1710 and multiple transmitter antennas 1715 and surface components such as processing unit 1705. Alternatively, the components can be co-located such as on one or more collars of a drill string or on a wireline structure.

In various embodiments, peripheral devices 1745 include displays, additional storage memory, and/or other control devices that may operate in conjunction with controller 1702 and/or memory 1725. In an embodiment, controller 1702 is a processor. A peripheral device arranged as a display can be

used with instructions stored in memory 1725 to implement a user interface to manage the operation of processing unit 1705, one or more tilted receiver antennas 1710, multiple transmitter antennas 1715 in system 1700 and/or components distributed within system 1700.

Figure 18 depicts an embodiment of a system 1800 at a drilling site, where system 1800 includes a measurement tool 1810 and electronics to determine formation properties in the vicinity of a well and/or geosignals that can be used for geosteering a drilling operation. Measurement tool 1810 can include one or more tilted receiver antennas and multiple transmitter antennas, where the transmitter antennas are fired independently such that measured signals received at the tilted receiver antennas are processed to directly determine a coupling matrix relative to propagation of electromagnetic signals in the formation in the vicinity of a borehole. The coupling matrix can be used to determine formation properties such as horizontal resistivity, vertical resistivity, and relative dip angle at any borehole deviation from the solution of the coupling voltage matrix determined form the measured signals, along with generating geosignals that can be used conduct geosteering with respect to the borehole.

System 1800 can include a drilling rig 1802 located at a surface 1804 of a well 1806 and a string of drill pipes, that is, drill string 1808, connected together so as to form a drilling string that is lowered through a rotary table 1807 into a wellbore or borehole 1812. The drilling rig 1802 can provide support for drill string 1808. The drill string 1808 can operate to penetrate rotary table 1807 for drilling a borehole 1812 through subsurface formations 1814. The drill string 1808 can include drill pipe 1818 and a bottom hole assembly 1820 located at the lower portion of the drill pipe 1818.

The bottom hole assembly 1820 can include drill collar 1815, a measuring tool 1810 attached to drill collar 1815, and a drill bit 1826. The drill bit 1826 can operate to create a borehole 1812 by penetrating the surface 1804 and subsurface formations 1814.

During drilling operations, the drill string 1808 can be rotated by the rotary table 1807. In addition to, or alternatively, the bottom hole assembly 1820 can also be rotated by a motor (e.g., a mud motor) that is located downhole. The drill collars 1815 can be used to add weight to the drill bit 1826. The drill collars 1815

also can stiffen the bottom hole assembly 1820 to allow the bottom hole assembly 1820 to transfer the added weight to the drill bit 1826, and in turn, assist the drill bit 1826 in penetrating the surface 1804 and subsurface formations 1814.

During drilling operations, a mud pump 1832 can pump drilling fluid (sometimes known by those of skill in the art as "drilling mud") from a mud pit 1834 through a hose 1836 into the drill pipe 1818 and down to the drill bit 1826. The drilling fluid can flow out from the drill bit 1826 and be returned to the surface 1804 through an annular area 1840 between the drill pipe 1818 and the sides of the borehole 1812. The drilling fluid may then be returned to the mud pit 1834, where such fluid is filtered. In some embodiments, the drilling fluid can be used to cool the drill bit 1826, as well as to provide lubrication for the drill bit 1826 during drilling operations. Additionally, the drilling fluid may be used to remove subsurface formation 1814 cuttings created by operating the drill bit 1826.

Various embodiments of techniques described herein process measured signals received at one or more tilted receiver antennas in response to firing multiple transmitter antennas independently to directly determine a coupling matrix relative to propagation of electromagnetic signals in the formation in the vicinity of a well hole due to the firing of multiple transmitter antennas. A processing unit can process signals acquired from one or more tilted receiver antennas based on the direction relative to rotation of the tool on which one or more tilted receiver antennas and multiple transmitter antennas are mounted. Processing unit can perform processing identical to or similar to the processing schemes discussed with respect to various embodiments herein.

Although specific embodiments have been illustrated and described herein, it will be appreciated by those of ordinary skill in the art that any arrangement that is calculated to achieve the same purpose may be substituted for the specific embodiments shown. Various embodiments use permutations and/or combinations of embodiments described herein. It is to be understood that the above description is intended to be illustrative, and not restrictive, and that the phraseology or terminology employed herein is for the purpose of description. Combinations of the above embodiments and other embodiments will be apparent to those of skill in the art upon studying the above description.

CLAIMS

What is claimed is:

1. A method of determining properties associated with operating in a borehole of a well, the method comprising:

acquiring signals generated from operating a tool rotating in the borehole, the tool having a longitudinal axis, the tool including two transmitter antennas and a receiver antenna tilted with respect to the longitudinal axis, the acquired signals including signals received at the tilted receiver antenna in response to firing separately the two transmitter antennas associated with the tilted receiver antenna; and

operating a processing unit to process the acquired signals with respect to a direction in the rotation of the tool to determine properties associated with a formation, including determining a coupling matrix directly from the acquired signals.

2. The method of claim 1, wherein acquiring signals includes acquiring voltage signals generated from operating the tool with the receiver antenna tilted with respect to the longitudinal axis and the two transmitter antennas placed essentially at the same location with different orientations.

3. The method of claim 1, wherein acquiring signals includes acquiring voltage signals generated from operating the tool with the receiver antenna tilted with respect to the longitudinal axis such that the tilted receiver antenna is placed between the two transmitters with the two transmitters having different orientations.

4. The method of claim 1, wherein acquiring signals includes acquiring voltage signals generated from operating the tool with the receiver antenna tilted with respect to the longitudinal axis and with another receiver antenna tilted with respect to the longitudinal axis and with the two receiver antennas placed between the two transmitter antennas, the two transmitter antennas having different

orientations.

5. The method of claim 4, wherein the method includes generating two coupling voltage matrices from received voltage signals at the two tilted receivers.

6. The method of claim 4, wherein, with respect to the longitudinal axis, one of the two transmitters is tilted at 45 degrees and the other transmitter antenna is tilted at -45 degrees and the two receivers are tilted at an angle of 45 degrees.

7. The method of claim 4, wherein acquiring signals and operating the processor unit includes:

firing one of the two transmitters and measuring a response at the tilted receiver with respect to the firing;

firing the other transmitter and measuring a response at the other tilted receiver with respect to the firing of the other transmitter; and

calculating coupling voltage components for the coupling matrix using the measured responses received at the two tilted receivers with respect to tool position and tool orientation; and

performing one or more inversion operations to generate formation parameters from the coupling matrix.

8. The method of claim 1, wherein each the two transmitter antennas have a tilt orientation with respect to the longitudinal axis such that the tilt orientations of the two transmitter antennas are in adjacent quadrants with respect to the longitudinal axis.

9. The method of claim 1, wherein acquiring signals includes acquiring voltage signals with respect to tool orientation, the tool orientation including a number of directions, the total number of directions corresponding to one complete rotation partitioned into N bins, each bin associated with an angle of rotation equal to $2\pi/N$, N being an integer equal to or greater than one.

10. The method of claim 1, wherein the method includes determining

horizontal resistivity, vertical resistivity, relative dip angle, or combinations thereof from the coupling matrix.

11. The method of claim 1, wherein acquiring signals includes acquiring voltage signals generated from operating the tool rotating in the borehole with the receiver antenna operated as a transmitting antenna and the two transmitter antennas tilted and operated as receiver antennas.

12. A method of determining properties associated with operating in a borehole of a well, the method comprising:

acquiring signals generated from operating a tool rotating in the borehole, the tool having a longitudinal axis, the tool including a receiver antenna tilted with respect to the longitudinal axis and two transmitter antennas, the acquired signals including signals received at the tilted receiver antenna in response to firing separately the two transmitter antennas associated with the tilted receiver antenna; and

operating a processing unit to process the acquired signals with respect to a direction in the rotation of the tool to determine properties associated with a formation, including determining a geosignal response directly from the acquired signals.

13. The method of claim 12, wherein the method includes geosteering of a drill operation based on the geosignal response.

14. The method of claim 12, wherein determining a geosignal response from the acquired signals includes generating the geosignal response as a geosignal phase and a geosignal attenuation.

15. The method of claim 14, wherein the method includes:

partitioning the tool rotation into N bins in which completion of the N bins is one complete rotation, $N \geq 2$;

generating, for a bin, the geosignal phase as the difference between a phase of a voltage signal received at the tilted receiver in response to firing one

transmitter for the bin and a phase of a voltage signal received at the tilted receiver in response to firing the one transmitter at another bin that is 180 degrees from the bin; and

generating, for the bin, the geosignal attenuation as the difference between the log of the voltage signal received at the tilted receiver in response to firing the one transmitter for the bin and the log of the voltage signal received at the tilted receiver in response to firing the one transmitter at another bin that is 180 degrees from the bin.

16. The method of claim 14, wherein the method includes:

partitioning the tool rotation into N bins in which completion of the N bins is one complete rotation of the tool, N $\geq$2, each bin having an associated azimuthal angle β;

generating, for a bin at azimuthal angle β, one or both of two geosignals, the two geosignals being:

$$V_{Geo}^{ZX}(\beta) \equiv \frac{V_R^U(\beta)+V_R^L(\beta+\pi)}{\frac{1}{N}\sum_{i=1}^{N}\left[V_R^U\left(\frac{\beta_m}{2}+(i-1)\times\beta_i\right)+V_R^L\left(\frac{\beta_m}{2}+(i-1)\times\beta_i\right)\right]}$$

and

$$V_{Geo}^{XZ}(\beta) \equiv \frac{V_R^U(\beta+\pi)+V_R^L(\beta+\pi)}{\frac{1}{N}\sum_{i=1}^{N}\left[V_R^U\left(\frac{\beta_m}{2}+(i-1)\times\beta_i\right)+V_R^L\left(\frac{\beta_m}{2}+(i-1)\times\beta_i\right)\right]}$$

where $V_{Geo}^{ZX}(\beta)$ and $V_{Geo}^{XZ}(\beta)$ are the two geosignals at the bin at azimuthal angle β, $V_R^U(\beta)$ is a voltage signal at the bin at azimuthal angle β received at the tilted receiver in response to firing one of the transmitters placed above the tilted receiver, $V_R^L(\beta)$ is a voltage signal received at the tilted receiver in response to firing the other transmitter placed below the tilted receiver, $V_R^U(\beta+\pi)$ is a voltage signal at another bin 180 degrees from the bin at azimuthal angle β received at the tilted receiver in response to firing one of the transmitters placed above the tilted receiver, $V_R^L(\beta+\pi)$ is a voltage signal at the other bin 180 degrees from the bin at azimuthal angle β received at the tilted receiver in response to firing the other transmitter placed below the tilted receiver, and the summation includes a voltage signal, for each bin, received at the tilted receiver in response to firing one of the

transmitters placed above the tilted receiver and a voltage signal, for each bin, received at the tilted receiver in response to firing the other transmitter placed below the tilted receiver.

17. A machine-readable medium that stores instructions, which when performed by a machine, cause the machine to perform operations, the operations comprising:

acquiring signals generated from operating a tool rotating in a borehole of a well, the tool having a longitudinal axis, the tool including a receiver antenna tilted with respect to the longitudinal axis and two transmitter antennas, the acquired signals including signals received at the tilted receiver antenna in response to firing separately the two transmitter antennas associated with the tilted receiver antenna; and

operating a processing unit to process the acquired signals with respect to a direction in the rotation of the tool to determine properties associated with a formation, including determining a coupling matrix from the acquired signals.

18. The machine-readable medium of claim 17, wherein acquiring signals includes acquiring voltage signals generated from operating the tool with the receiver antenna tilted with respect to the longitudinal axis and with another receiver antenna tilted with respect to the longitudinal axis, the two receivers tilted at an angle of 45 degrees with the two receiver antennas placed between the two transmitter antennas, the two transmitter antennas oriented with respect to the longitudinal axis such that one of the two transmitters is tilted at 45 degrees and the other transmitter antenna is tilted at -45 degrees.

19. The machine-readable medium of claim 17, wherein the instructions include determining horizontal resistivity, vertical resistivity, relative dip angle, or combinations thereof from the coupling matrix.

20. The machine-readable medium of claim 17, wherein the instructions include determining a geosignal response from the acquired signals and geosteering of a drill operation based on the geosignal response.

21. The machine-readable medium of claim 17, wherein the instructions include:

partitioning the tool rotation into N bins in which completion of the N bins is one complete rotation of the tool, N ≥2, each bin having an associated azimuthal angle β; and

determining a geosignal response from the acquired signals for a bin, the geosignal response being generated as one or more of:

a geosignal phase and a geosignal attenuation, the geosignal phase as the difference between a phase of a voltage signal received at the tilted receiver in response to firing one transmitter for the bin and a phase of a voltage signal received at the tilted receiver in response to firing the one transmitter at another bin that is 180 degrees from the bin and the geosignal attenuation as the difference between the log of the voltage signal received at the tilted receiver in response to firing the one transmitter for the bin and the log of the voltage signal received at the tilted receiver in response to firing the one transmitter at another bin that is 180 degrees from the bin,

$$V_{Geo}^{ZX}(\beta) \equiv \frac{V_R^U(\beta)+V_R^L(\beta+\pi)}{\frac{1}{N}\sum_{i=1}^{N}\left[V_R^U\left(\frac{\beta_m}{2}+(i-1)\times\beta_i\right)+V_R^L\left(\frac{\beta_m}{2}+(i-1)\times\beta_i\right)\right]},$$

or

$$V_{Geo}^{XZ}(\beta) \equiv \frac{V_R^U(\beta+\pi)+V_R^L(\beta+\pi)}{\frac{1}{N}\sum_{i=1}^{N}\left[V_R^U\left(\frac{\beta_m}{2}+(i-1)\times\beta_i\right)+V_R^L\left(\frac{\beta_m}{2}+(i-1)\times\beta_i\right)\right]}$$

where $V_{Geo}^{ZX}(\beta)$ and $V_{Geo}^{XZ}(\beta)$ are the two geosignals at the bin at azimuthal angle β, $V_R^U(\beta)$ is a voltage signal at the bin at azimuthal angle β received at the tilted receiver in response to firing one of the transmitters placed above the tilted receiver, $V_R^L(\beta)$ is a voltage signal received at the tilted receiver in response to firing the other transmitter placed below the tilted receiver, $V_R^U(\beta+\pi)$ is a voltage signal at another bin 180 degrees from the bin at azimuthal angle β received at the tilted receiver in response to firing one of the transmitters placed above the tilted receiver, $V_R^L(\beta+\pi)$

is a voltage signal at the other bin 180 degrees from the bin at azimuthal angle β received at the tilted receiver in response to firing the other transmitter placed below the tilted receiver, and the summation includes a voltage signal, for each bin, received at the tilted receiver in response to firing one of the transmitters placed above the tilted receiver and a voltage signal, for each bin, received at the tilted receiver in response to firing the other transmitter placed below the tilted receiver.

22. An apparatus comprising:

a tool operable to rotate in the borehole, the tool having a longitudinal axis, the tool including a receiver antenna tilted with respect to the longitudinal axis and two transmitter antennas, the tilted receiver antenna arranged to acquire signals in response to firing separately the two transmitter antennas; and

a processing unit to process the acquired signals with respect to a direction in the rotation of the tool, to determine a coupling matrix directly from the acquired signals, and to determine properties associated with a formation.

23. The apparatus of claim 22, wherein the two transmitter antennas are placed essentially at the same location with different orientations.

24. The apparatus of claim 22, wherein the tilted receiver antenna is placed between the two transmitters with the two transmitters having different orientations.

25. The apparatus of claim 22, wherein the tool includes another receiver antenna tilted with respect to the longitudinal axis with the two receiver antennas placed between the two transmitter antennas, the two transmitter antennas having different orientations.

26. The apparatus of claim 25, wherein the processing unit includes machine readable instructions executable by a processor to generate two coupling voltage matrices from received voltage signals at the two tilted receivers.

27. The apparatus of claim 25, wherein, with to the longitudinal axis, one of the two transmitters is tilted at 45 degrees and the other transmitter antenna is tilted at -45 degrees and the two receivers are tilted at an angle of 45 degrees.

28. The apparatus of claim 22, wherein each the two transmitter antennas have a tilt orientation with respect to the longitudinal axis such that the tilt orientation of the two transmitter antennas are in adjacent quadrants with respect to the longitudinal axis.

29. The apparatus of claim 22, wherein the processing unit includes machine readable instructions executable by a processor to determine horizontal resistivity, vertical resistivity, relative dip angle, or combinations thereof from the coupling matrix.

30. The apparatus of claim 22, wherein the processing unit includes machine readable instructions executable by a processor to determine a geosignal response from the acquired signals and to geosteer a drill operation based on the geosignal response.

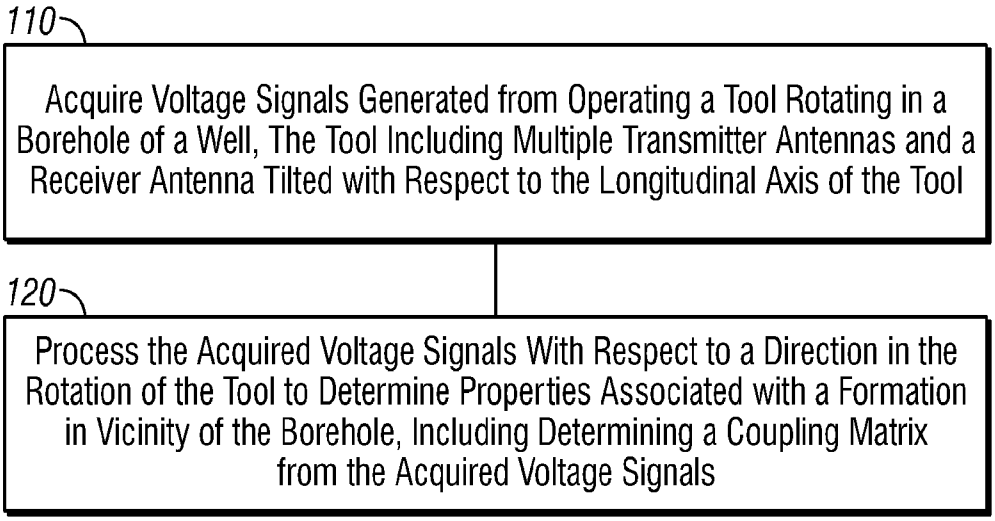

110
Acquire Voltage Signals Generated from Operating a Tool Rotating in a Borehole of a Well, The Tool Including Multiple Transmitter Antennas and a Receiver Antenna Tilted with Respect to the Longitudinal Axis of the Tool
120
Process the Acquired Voltage Signals With Respect to a Direction in the Rotation of the Tool to Determine Properties Associated with a Formation in Vicinity of the Borehole, Including Determining a Coupling Matrix from the Acquired Voltage Signals

FIG. 1

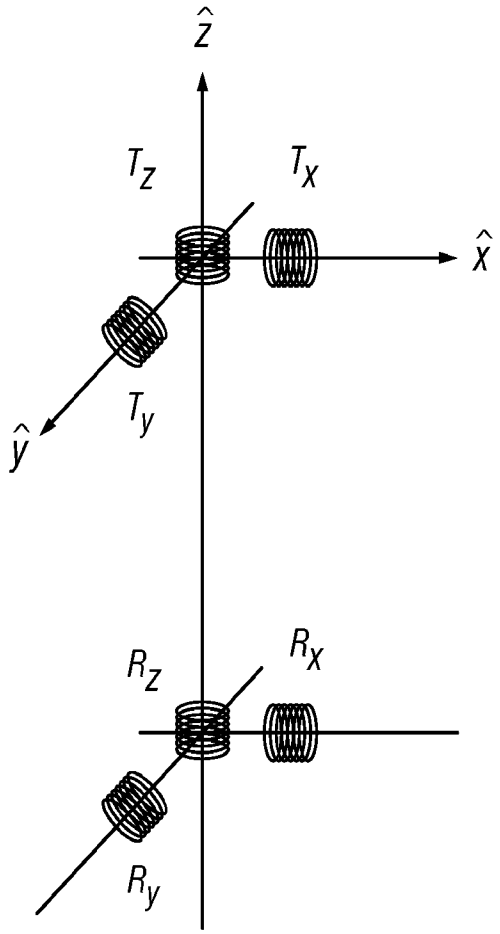

$\hat{z}$
T_Z
T_X
$\hat{x}$
T_y
$\hat{y}$
R_Z
R_X
R_y

FIG. 2

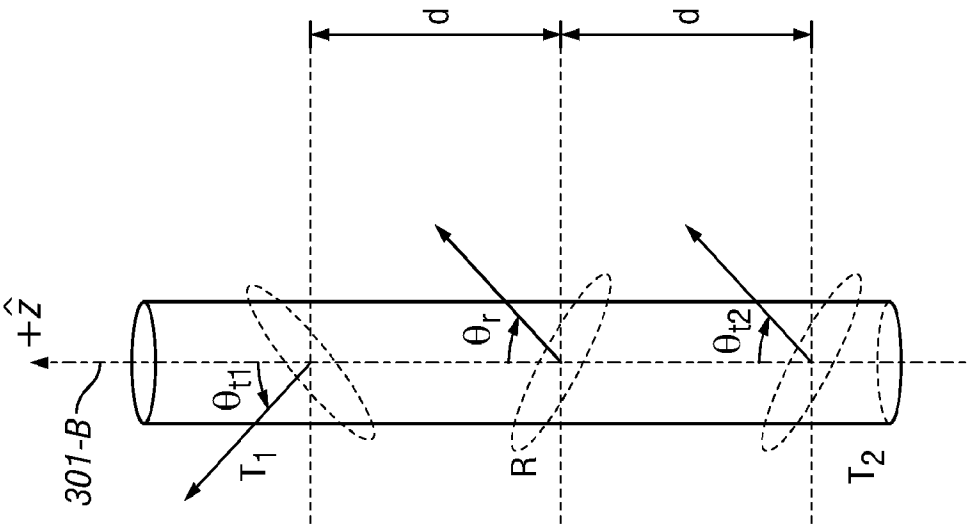


FIG. 3B

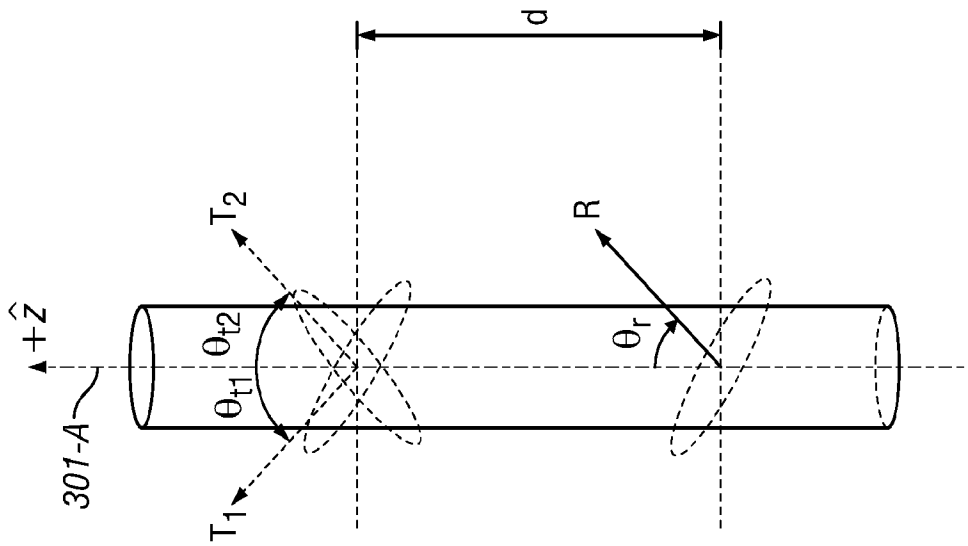


FIG. 3A

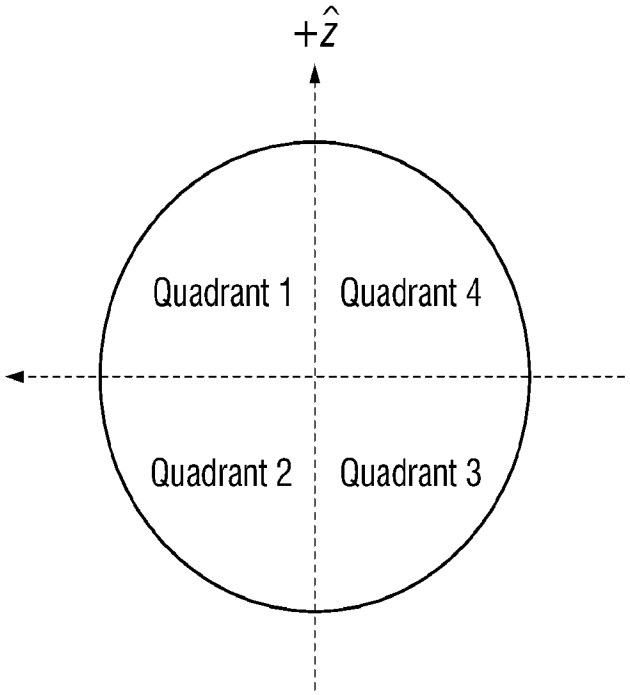

+ẑ
Quadrant 1
Quadrant 4
Quadrant 2
Quadrant 3

FIG. 3C

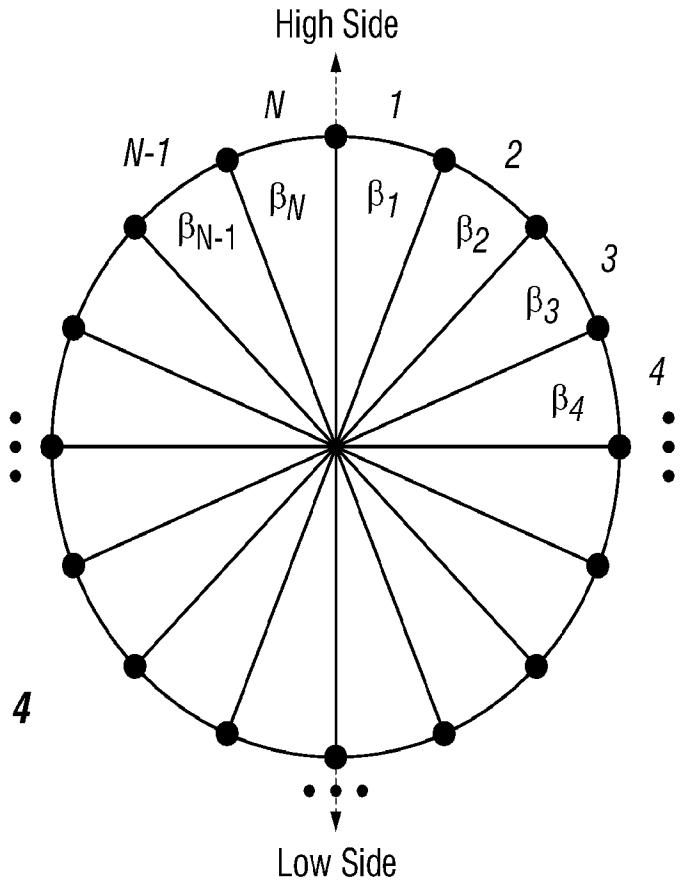

High Side
N
1
2
3
4
N-1
βN
β1
β2
β3
β4
βN-1
Low Side

FIG. 4

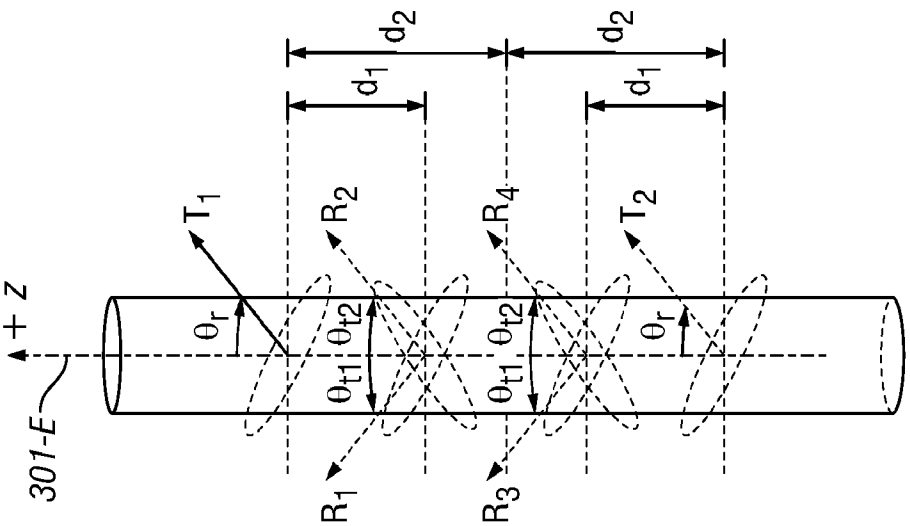

301-E
+ ẑ
θr
θt1
θt2
T1
R2
R4
T2
R1
R3
d1
d2

FIG. 3E

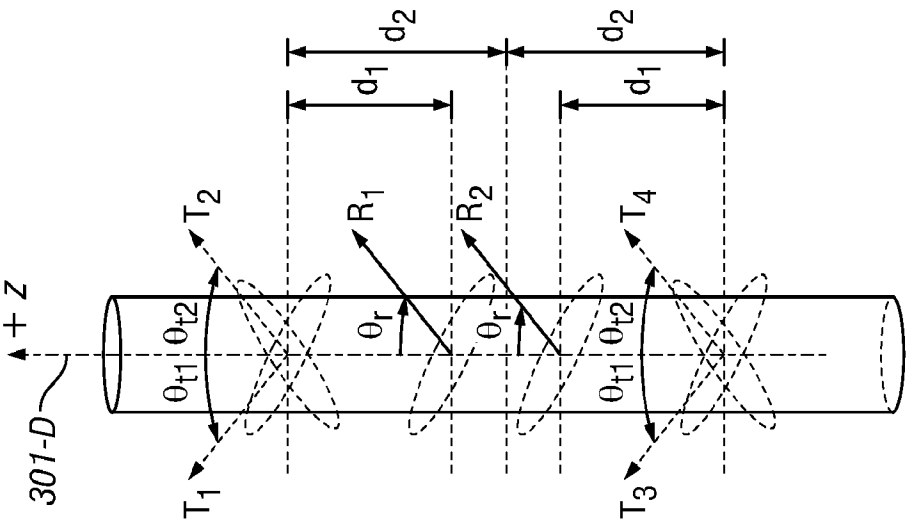

301-D
+ ẑ
θr
θt1
θt2
T2
R1
R2
T4
T1
T3
d1
d2

FIG. 3D

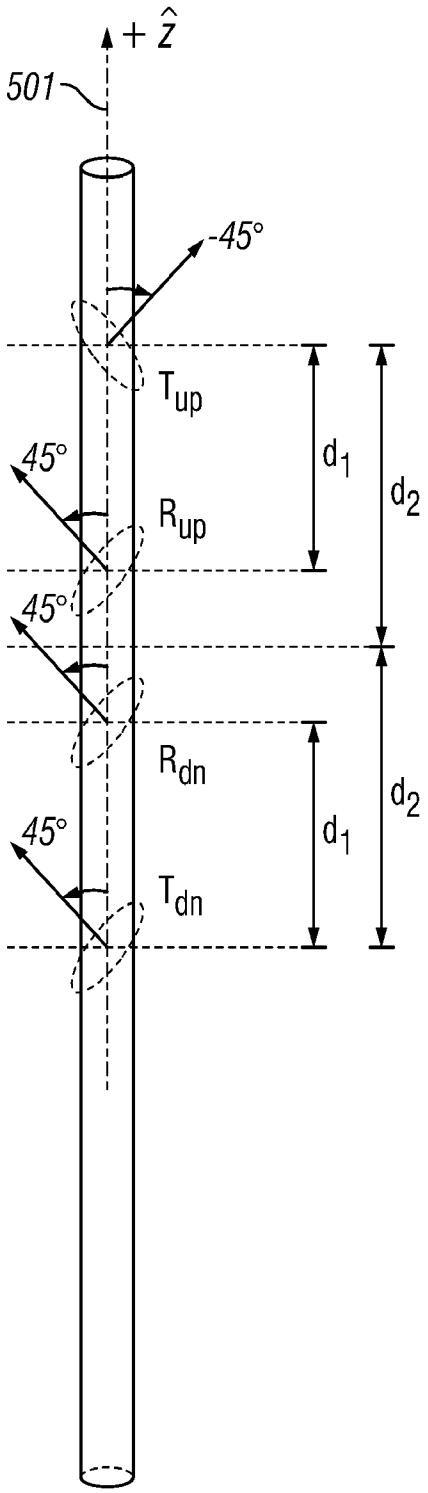


FIG. 5

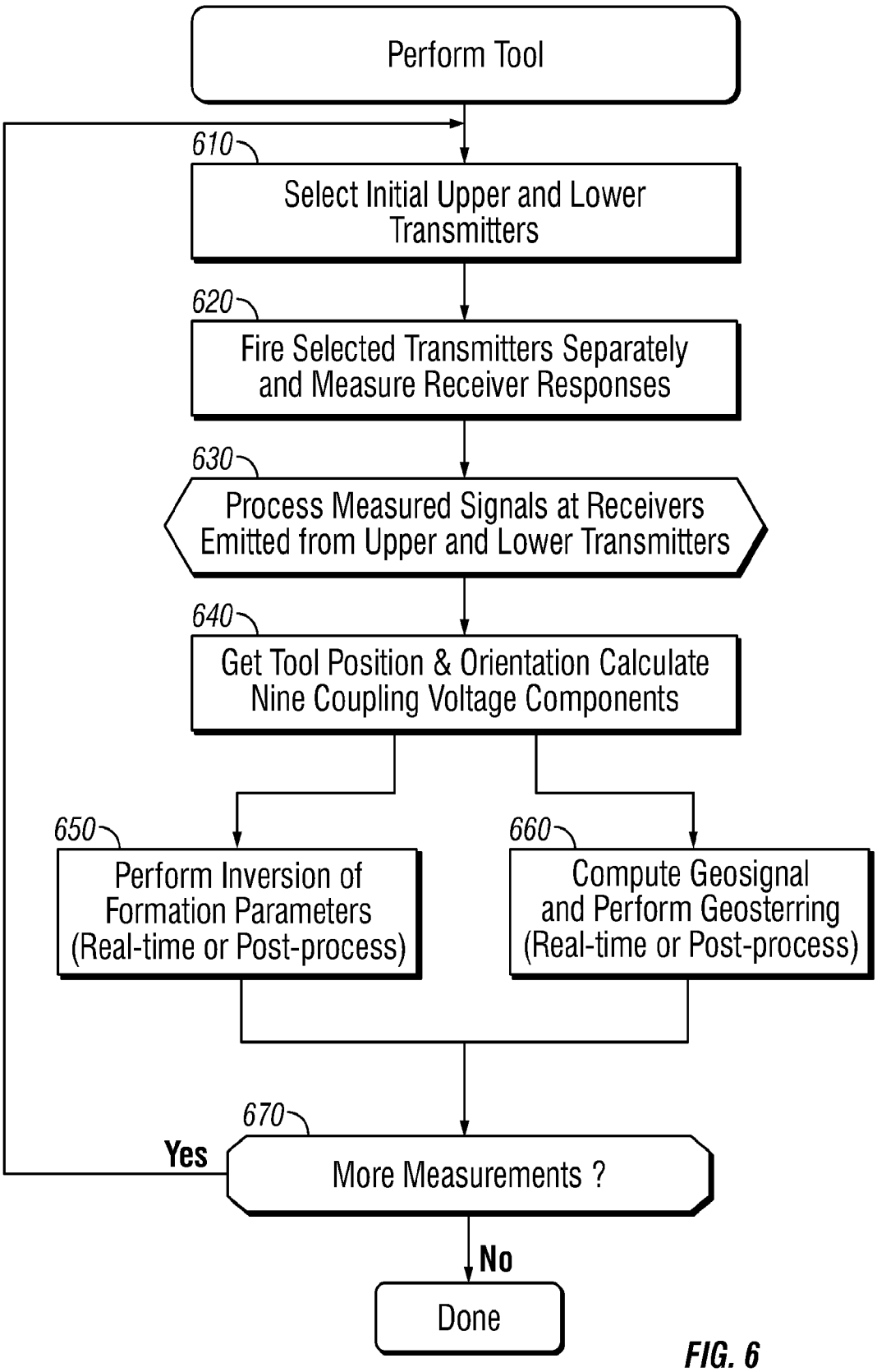

Perform Tool
610
Select Initial Upper and Lower Transmitters
620
Fire Selected Transmitters Separately and Measure Receiver Responses
630
Process Measured Signals at Receivers Emitted from Upper and Lower Transmitters
640
Get Tool Position & Orientation Calculate Nine Coupling Voltage Components
650
Perform Inversion of Formation Parameters (Real-time or Post-process)
660
Compute Geosignal and Perform Geosterring (Real-time or Post-process)
670
Yes
More Measurements ?
No
Done

FIG. 6

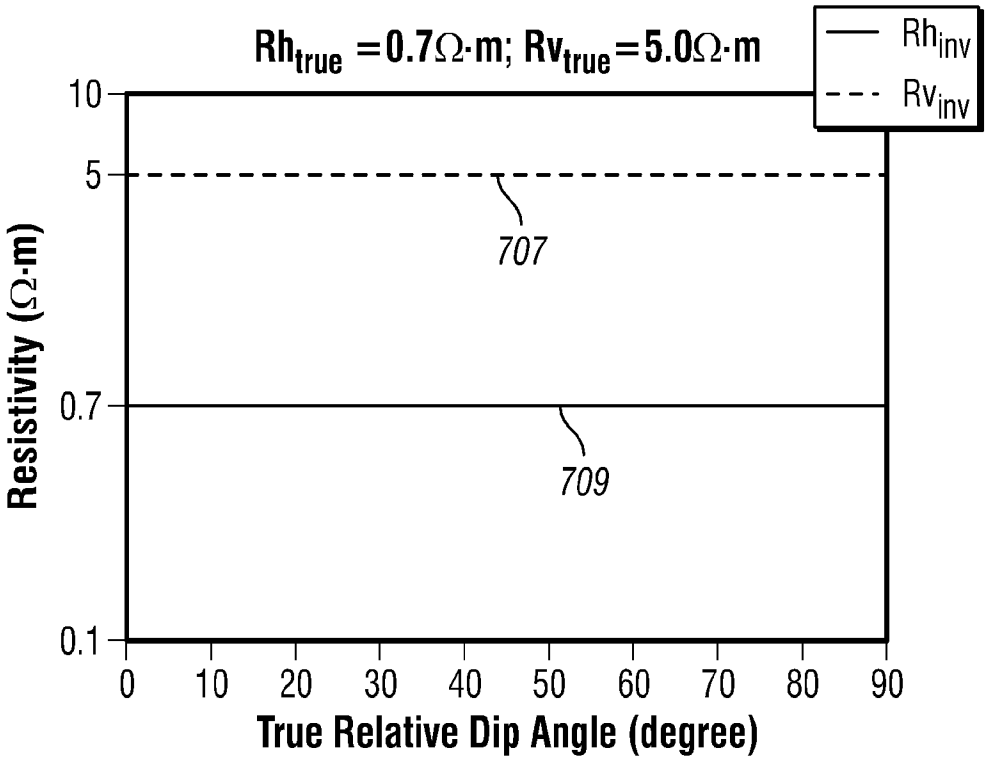

Rh_true =0.7Ω·m; Rv_true=5.0Ω·m
Rh_inv
Rv_inv
10
5
0.7
0.1
Resistivity (Ω·m)
707
709
0
10
20
30
40
50
60
70
80
90
True Relative Dip Angle (degree)

FIG. 7A

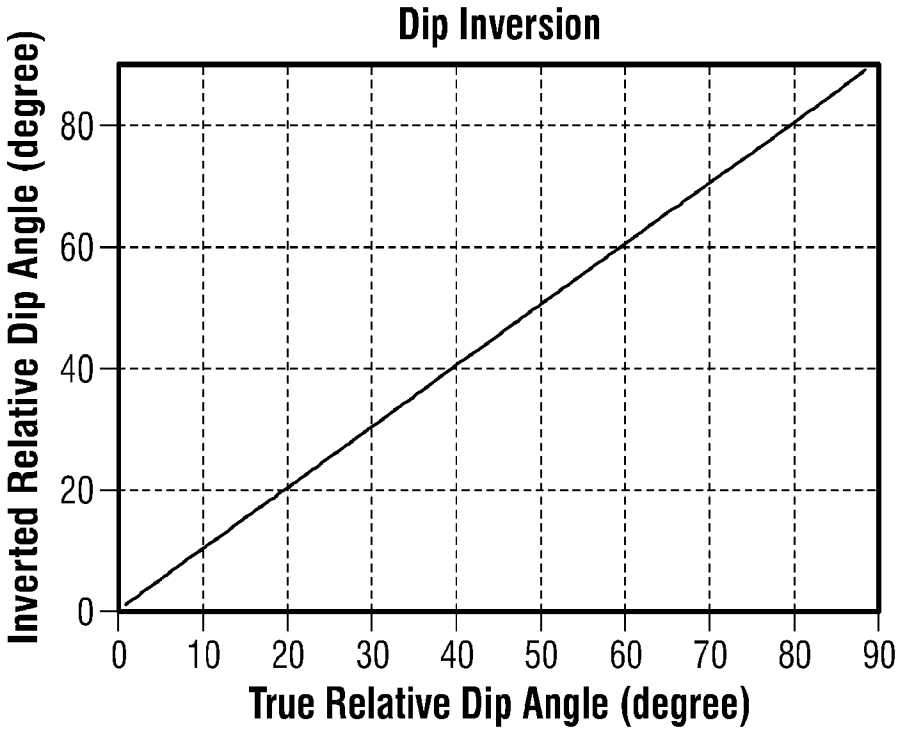

Dip Inversion
Inverted Relative Dip Angle (degree)
80
60
40
20
0
0
10
20
30
40
50
60
70
80
90
True Relative Dip Angle (degree)

FIG. 7B

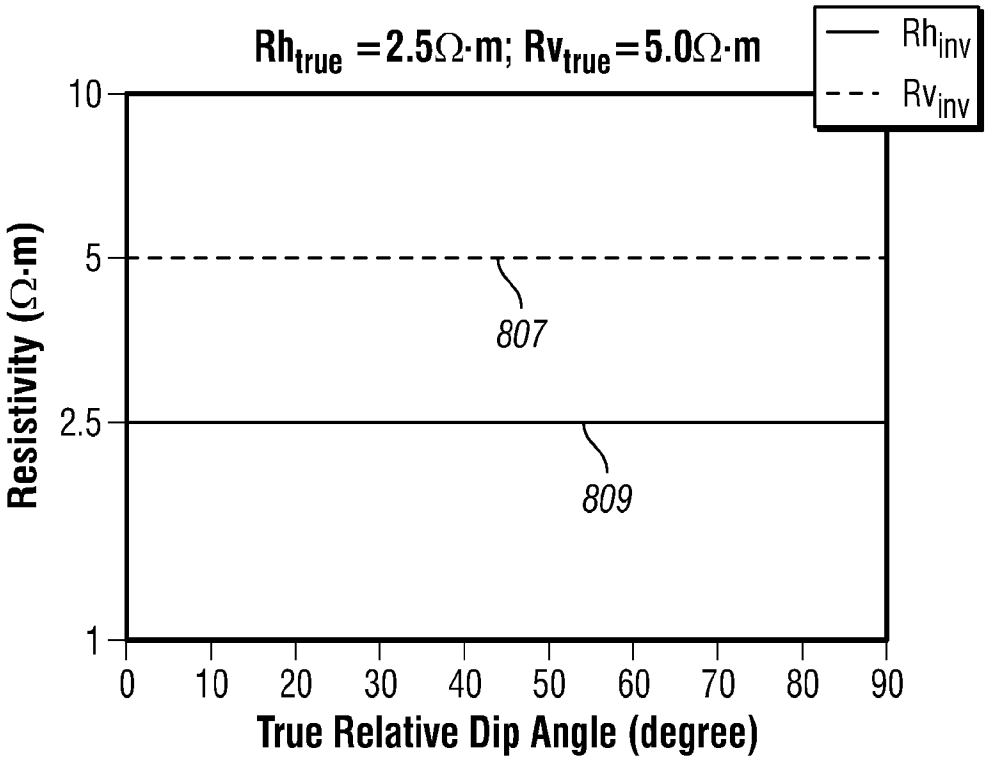

Rh_true =2.5Ω·m; Rv_true=5.0Ω·m
Rh_inv
Rv_inv
Resistivity (Ω·m)
10
5
2.5
1
807
809
0
10
20
30
40
50
60
70
80
90
True Relative Dip Angle (degree)

FIG. 8A

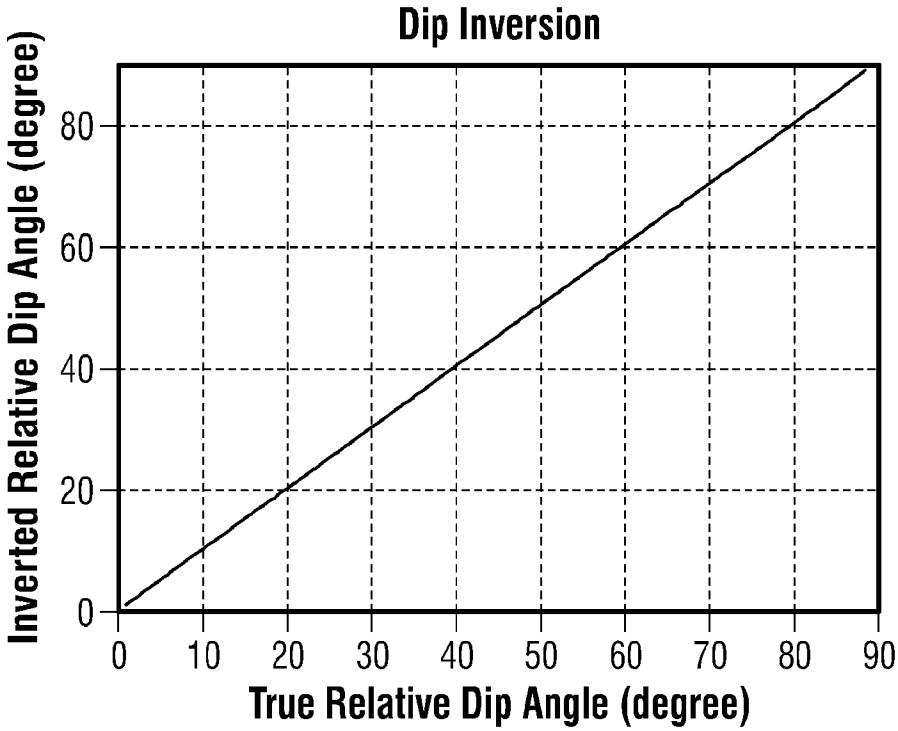

Dip Inversion
Inverted Relative Dip Angle (degree)
80
60
40
20
0
0
10
20
30
40
50
60
70
80
90
True Relative Dip Angle (degree)

FIG. 8B

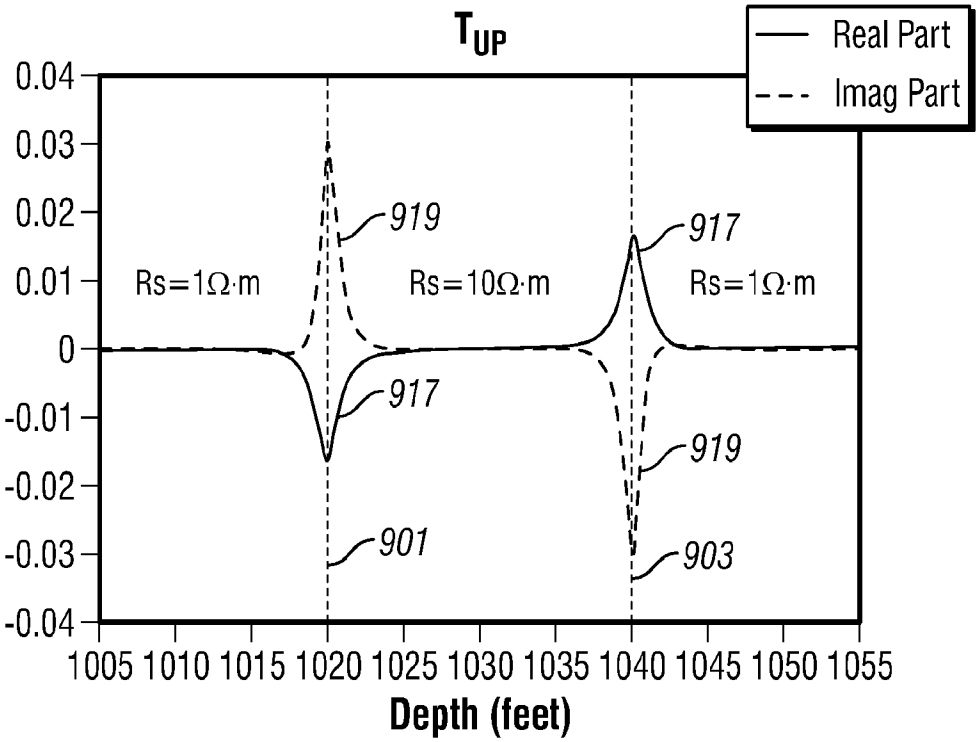

T_{UP}
Real Part
Imag Part
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
Rs=1Ω·m
Rs=10Ω·m
Rs=1Ω·m
919
917
917
919
901
903
1005 1010 1015 1020 1025 1030 1035 1040 1045 1050 1055
Depth (feet)

FIG. 9

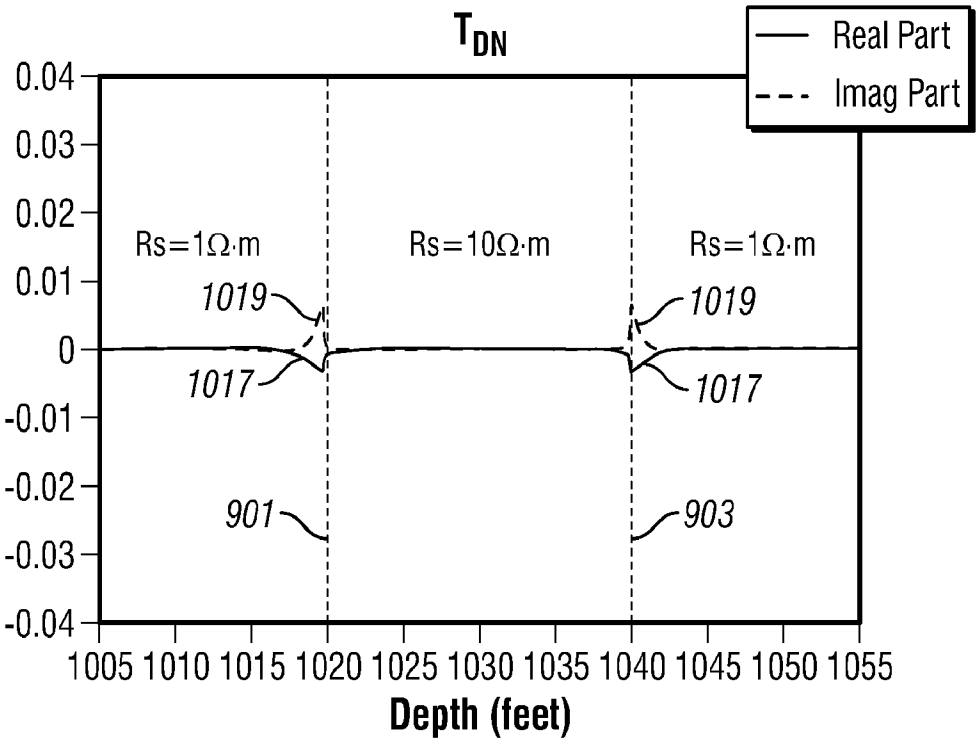

T_{DN}
Real Part
Imag Part
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
Rs=1Ω·m
Rs=10Ω·m
Rs=1Ω·m
1019
1019
1017
1017
901
903
1005 1010 1015 1020 1025 1030 1035 1040 1045 1050 1055
Depth (feet)

FIG. 10

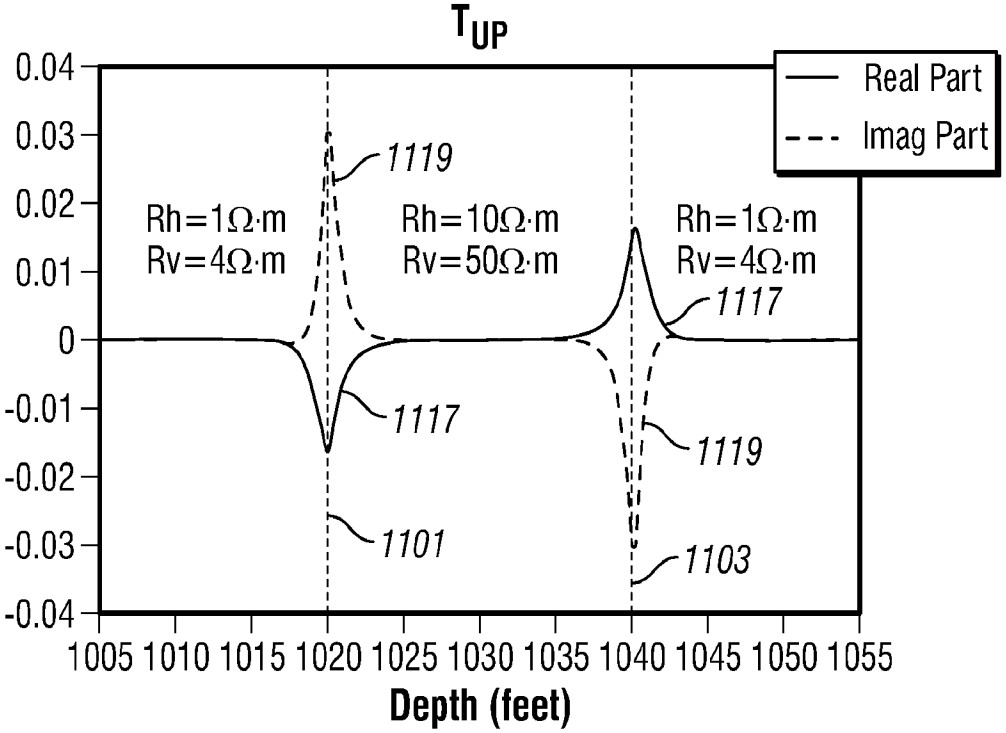

T_{UP}
Real Part
Imag Part
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
1119
Rh=1Ω·m
Rv=4Ω·m
Rh=10Ω·m
Rv=50Ω·m
Rh=1Ω·m
Rv=4Ω·m
1117
1117
1119
1101
1103
1005 1010 1015 1020 1025 1030 1035 1040 1045 1050 1055
Depth (feet)

FIG. 11

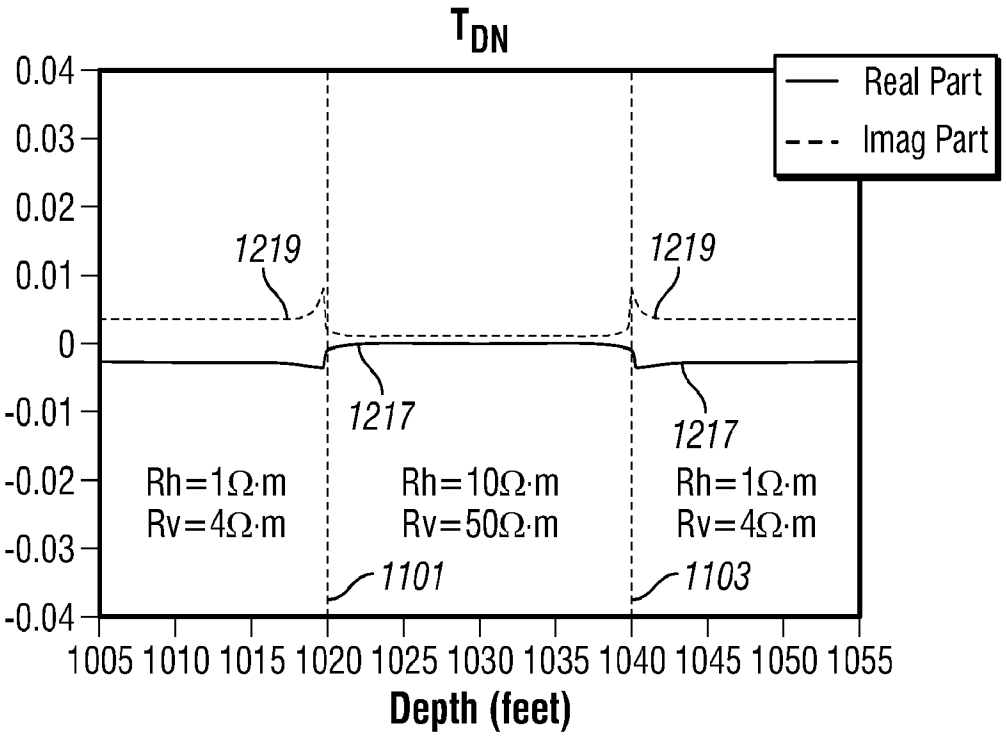

T_{DN}
Real Part
Imag Part
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
1219
1219
1217
1217
Rh=1Ω·m
Rv=4Ω·m
Rh=10Ω·m
Rv=50Ω·m
Rh=1Ω·m
Rv=4Ω·m
1101
1103
1005 1010 1015 1020 1025 1030 1035 1040 1045 1050 1055
Depth (feet)

FIG. 12

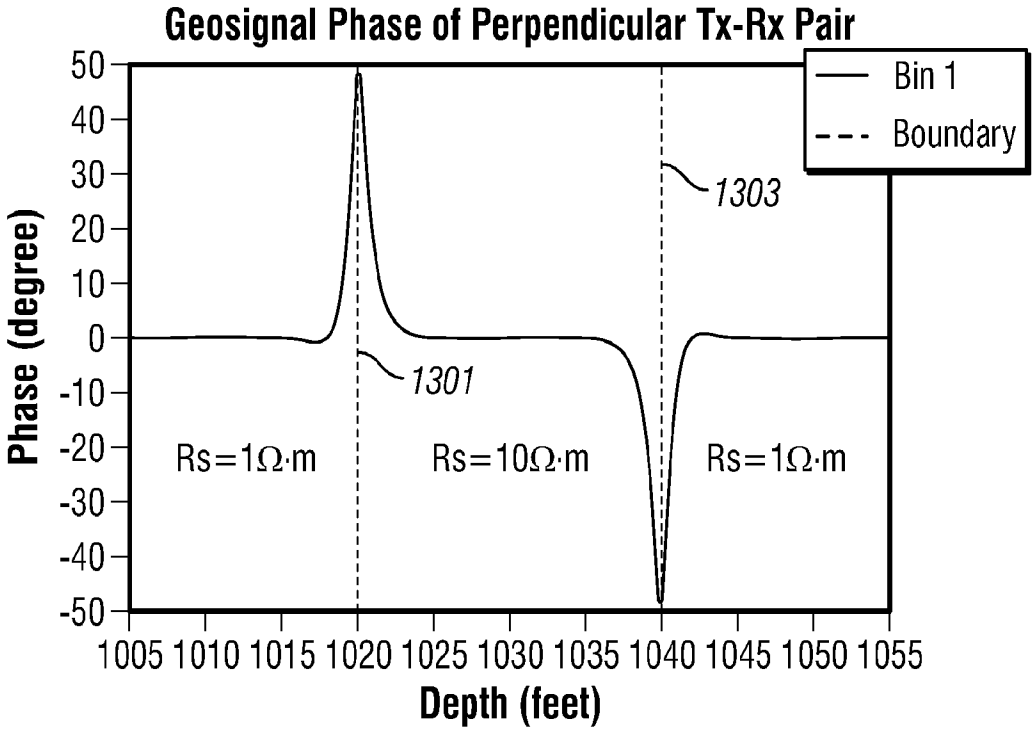

Geosignal Phase of Perpendicular Tx-Rx Pair
Phase (degree)
50
40
30
20
10
0
-10
-20
-30
-40
-50
Bin 1
Boundary
1303
1301
Rs=1Ω·m
Rs=10Ω·m
Rs=1Ω·m
1005 1010 1015 1020 1025 1030 1035 1040 1045 1050 1055
Depth (feet)

FIG. 13

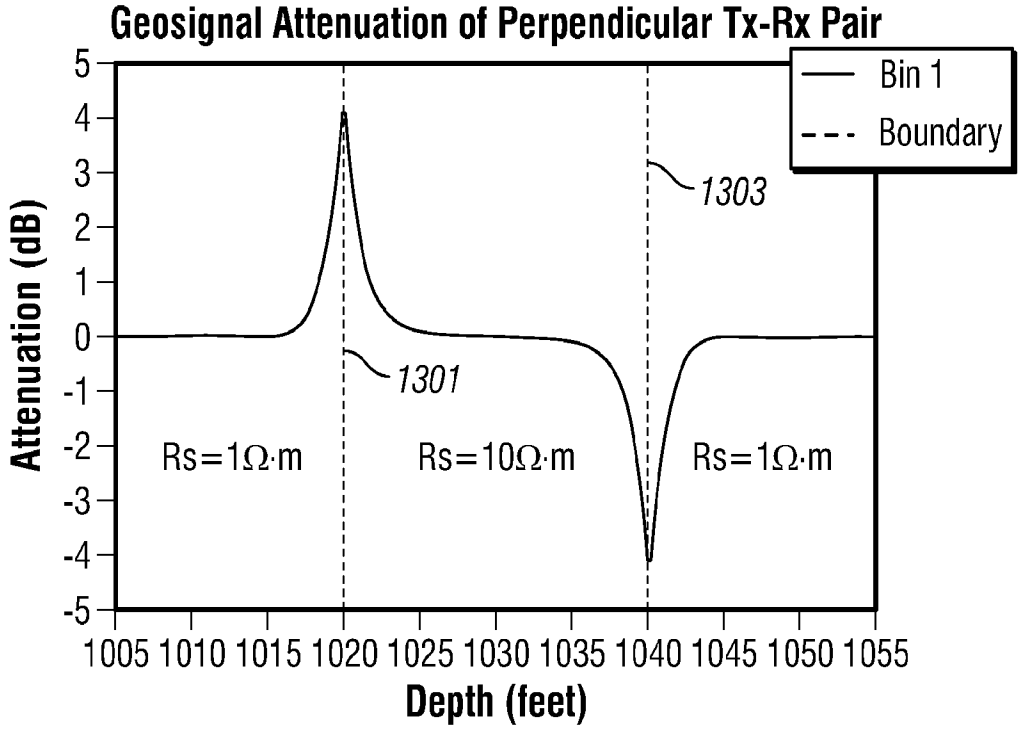

Geosignal Attenuation of Perpendicular Tx-Rx Pair
Attenuation (dB)
5
4
3
2
1
0
-1
-2
-3
-4
-5
Bin 1
Boundary
1303
1301
Rs=1Ω·m
Rs=10Ω·m
Rs=1Ω·m
1005 1010 1015 1020 1025 1030 1035 1040 1045 1050 1055
Depth (feet)

FIG. 14

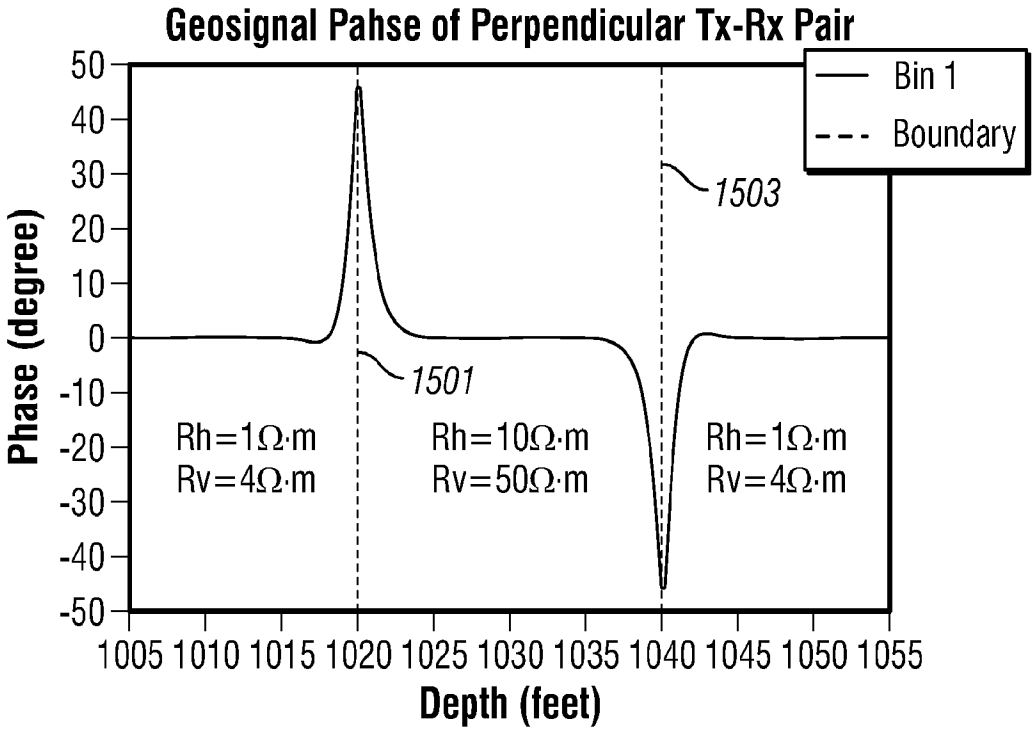

Geosignal Pahse of Perpendicular Tx-Rx Pair
Phase (degree)
50
40
30
20
10
0
-10
-20
-30
-40
-50
Bin 1
Boundary
1503
1501
Rh=1Ω·m
Rv=4Ω·m
Rh=10Ω·m
Rv=50Ω·m
Rh=1Ω·m
Rv=4Ω·m
1005 1010 1015 1020 1025 1030 1035 1040 1045 1050 1055
Depth (feet)

FIG. 15

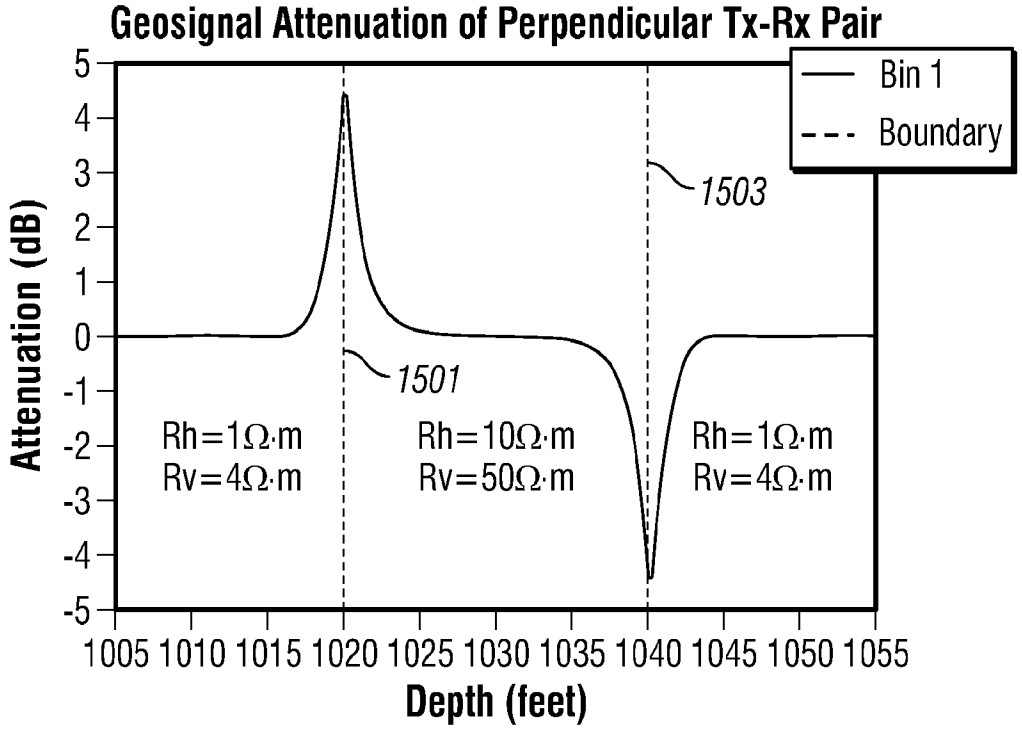

Geosignal Attenuation of Perpendicular Tx-Rx Pair
Attenuation (dB)
5
4
3
2
1
0
-1
-2
-3
-4
-5
Bin 1
Boundary
1503
1501
Rh=1Ω·m
Rv=4Ω·m
Rh=10Ω·m
Rv=50Ω·m
Rh=1Ω·m
Rv=4Ω·m
1005 1010 1015 1020 1025 1030 1035 1040 1045 1050 1055
Depth (feet)

FIG. 16

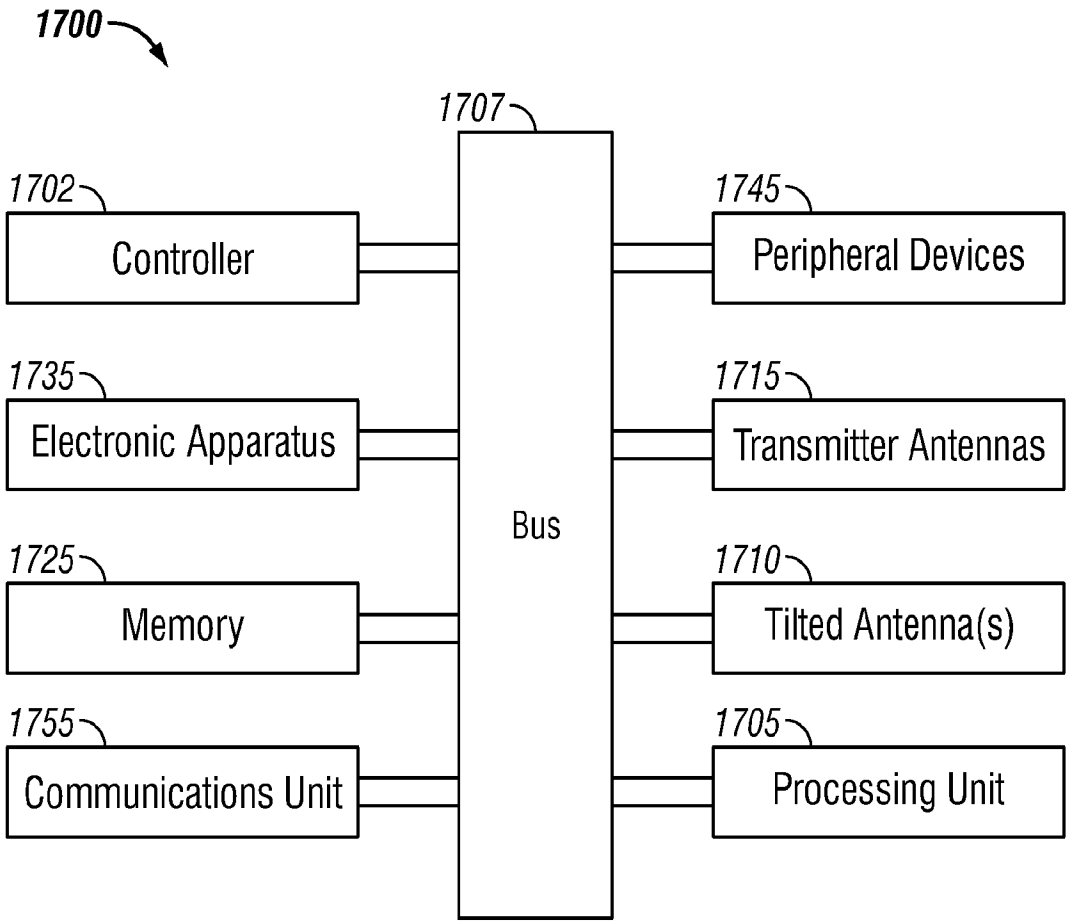

1700
1707
1702
Controller
1745
Peripheral Devices
1735
Electronic Apparatus
1715
Transmitter Antennas
Bus
1725
Memory
1710
Tilted Antenna(s)
1755
Communications Unit
1705
Processing Unit

FIG. 17

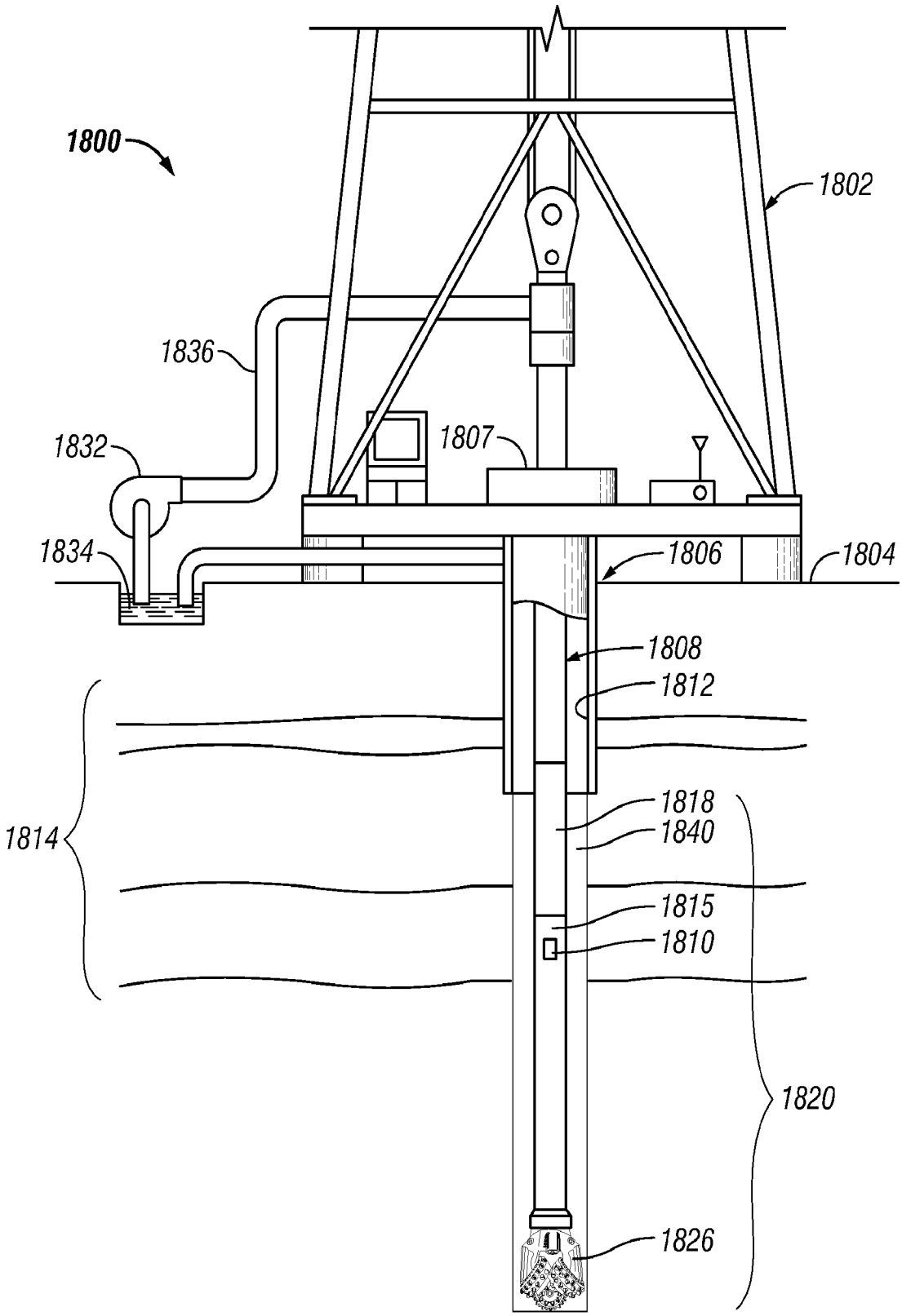

1800
1802
1836
1832
1807
1834
1806
1804
1808
1812
1814
1818
1840
1815
1810
1820
1826

FIG. 18

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2010/031243

A. CLASSIFICATION OF SUBJECT MATTER
INV. G01V3/28

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G01V E21C

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2008/076130 A1 (HALLIBURTON ENERGY SERV INC [US]; BITTAR MICHAEL [US]; HU GUOYU [US]) 26 June 2008 (2008-06-26) abstract page 4, line 4 - line 25; figures 1,8 page 7, line 17 - line 19; figure 7 page 14, line 21 - line 13 page 10, line 16 - line 19 Equation 3claim 11; figures 12,13 page 12, line 14 - line 24 page 13, line 1 - line 6 ----- -/--	1-11, 17-30

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
19 January 2011	06/04/2011

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Wehland, Florian

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2010/031243

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

see additional sheet

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☒ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

1-11, 17-30

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2010/031243

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2003/030439 A1 (GAO LI [US] ET AL) 13 February 2003 (2003-02-13) abstract paragraphs [0013] - [0014] paragraph [0030] - paragraph [0032] paragraph [0037] - paragraph [0042] paragraph [0064] claims 1,2,13-15	1-11, 17-30
A	US 2005/140373 A1 (LI QIMING [US] ET AL) 30 June 2005 (2005-06-30) abstract paragraphs [0003], [0010], [0017]; figures 3-6,11 paragraph [0020] - paragraph [0022] paragraphs [0025], [0038], [0044] claims 1,8,10	1-11, 17-30
A	WO 2008/115229 A1 (HALLIBURTON ENERGY SERV INC [US]; HU GUOYU [US]; BITTAR MICHAEL [US]) 25 September 2008 (2008-09-25) abstract page 10, paragraph 4; figures 6-11,17 page 11, paragraph 3 claims 1,4,6,10	1-11, 17-30

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2010/031243

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 2008076130 A1	26-06-2008	CN 101460698 A	17-06-2009
		EP 2066866 A1	10-06-2009
		US 2009230968 A1	17-09-2009
US 2003030439 A1	13-02-2003	AU 2002300176 B2	06-10-2005
		BR 0203118 A	27-05-2003
		CA 2397168 A1	09-02-2003
		GB 2382146 A	21-05-2003
		NO 20023758 A	10-02-2003
US 2005140373 A1	30-06-2005	BR PI0401805 A	18-01-2005
		CN 1573013 A	02-02-2005
		DE 102004024969 A1	05-01-2006
		FR 2859539 A1	11-03-2005
		FR 2855272 A1	26-11-2004
		GB 2402489 A	08-12-2004
		MX PA04004692 A	25-11-2004
WO 2008115229 A1	25-09-2008	AU 2007349251 A1	25-09-2008
		GB 2459067 A	14-10-2009
		US 2010156424 A1	24-06-2010

FURTHER INFORMATION CONTINUED FROM PCT/ISA/ 210

This International Searching Authority found multiple (groups of) inventions in this international application, as follows:

1. claims: 1-11, 17-30

   Method for determining properties in a borehole including the acquistion of data via a transmitter receiver system and a processing unit determining a coupling matrix from the received signals.

   ---

2. claims: 12-16

   Method for determining properties in a borehole including the acquistion of data via a transmitter receiver system and a processing unit determining a geosignal from the received signals.
