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

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
20 March 2014 (20.03.2014)

WIPO | PCT

(10) International Publication Number
WO 2014/043073 A2

(51) International Patent Classification:
E21B 47/09 (2012.01)

(21) International Application Number:
PCT/US2013/058908

(22) International Filing Date:
10 September 2013 (10.09.2013)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
61/701,118 14 September 2012 (14.09.2012) US
14/021,395 9 September 2013 (09.09.2013) US

(71) Applicant: **SCIENTIFIC DRILLING INTERNATIONAL, INC.** [US/US]; 16701 Greenspoint Park Dr., Suite 200, Houston, TX 77073 (US).

(72) Inventors: **TOWLE, James, N.**; c/o Scientific Drilling International, Inc., 16701 Greenspoint Park Dr., Suite 200, Houston, TX 77073 (US). **FAIRCHILD, Hans**; c/o Scientific Drilling International, Inc., 16701 Greenspoint Park Dr., Suite 200, Houston, TX 77073 (US).

(74) Agent: **LOCKLAR, Michael**; Adolph Locklar, 4615 SW Freeway, Suite 630, Houston, Texas 77027 (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, BN, 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, 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, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, 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, RW, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, 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, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— *without international search report and to be republished upon receipt of that report (Rule 48.2(g))*

WO 2014/043073 A2

(54) Title: EARLY DETECTION AND ANTI-COLLISION SYSTEM

(57) Abstract: An apparatus mechanically connected to a drill bit can include a bottom hole assembly having an MWD system, magnetic sensors, and a short range communications system. The short range communications system can be in electrical connection with the magnetic sensors. A method can include supplying a bottom hole assembly that includes an MWD system. The MWD system can have navigation sensors and acceleration sensors, magnetic sensors, and a short range communications system. The bottom hole assembly can be mechanically connected to a drill bit and the magnetic sensors can be within 10 feet of the bit. The method further includes measuring a magnetic field with the magnetic sensors and communicating the measurement of the magnetic field from the magnetic sensors to the MWD system through the short range communications system.

EARLY DETECTION AND ANTI-COLLISION SYSTEM

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is a non-provisional application which claims priority from U.S. provisional application number 61/701,118, filed September 14, 2012.

BACKGROUND OF THE DISCLOSURE

[0002] Field: This disclosure relates to a directional drilling and measurement system comprising magnetic and gravity sensors mounted on a downhole drilling mechanism and a data transmission system capable of calculating and transmitting to the surface certain magnetic field values and detection parameters for the purpose of detecting variations in the magnetic field ahead of and adjacent to the downhole drilling mechanism.

[0003] Background Discussion:

[0004] Drilling in a crowded underground space, such as in a field with earlier-drilled wellbores or multiple wells from a single pad or closely located pad, may present challenges in avoiding underground piping and other metallic objects. Previous surveys of the existing underground piping may be unavailable or inaccurate. Existing underground piping and other metallic objects have a magnetic field that may be detected (hereinafter an "underground magnetic source" or "magnetic source"). Determining the position and size of the magnetic source may not always be possible with existing equipment and techniques.

[0005] In addition to the difficulty in determining the position and size of the magnetic source, traditionally, magnetic means of determining the location of the magnetic source may be located a significant distance from a drill bit, often as much as 50 feet or more. Such distances can cause a delay in detection and location determination of the magnetic source, sometimes resulting in collisions. Collisions between the drill bit and a metallic object may result in damage to the drill bit and most often results in significant downtime.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] The present disclosure is best understood from the following detailed description when read with the accompanying figures. It is emphasized that, in accordance with the standard practice in the industry, various features are not drawn to scale. In fact, the dimensions of the various features may be arbitrarily reduced for clarity of discussion.

[0007] FIG. 1 is a depiction of a well installation consistent with certain embodiments of the present disclosure.

[0008] FIG. 2 is a schematic view of a bottom hole assembly consistent with certain embodiments of the present disclosure.

[0009] FIG. 3A is a cross-sectional view of a mud motor consistent with certain embodiments of the present disclosure.

[0010] FIG. 3B is a cross-sectional view of a mud motor consistent with certain embodiments of the present disclosure.

[0011] FIG. 3C is a cross-sectional view of a mud motor consistent with certain embodiments of the present disclosure.

[0012] FIG. 4A is a front elevation view of a mud motor consistent with certain embodiments of the present disclosure.

[0013] FIG. 4B is a side elevation view of a mud motor consistent with certain embodiments of the present disclosure.

[0014] FIG. 5 is a partial cross sectional view of a mud motor taken along section lines 4-4 of FIG. 4A consistent with certain embodiments of the present disclosure.

[0015] FIG. 5A is an exploded view of portions of the cross-sectional view of FIG. 5 of a mud motor consistent with certain embodiments of the present disclosure.

[0016] FIG. 6 is a sectional plan view taken along section lines 3-3 of FIG. 4A of a mud motor consistent with certain embodiments of the present disclosure.

[0017] FIG. 7 shows the general arrangement of an electric field pure conduction short range communications system consistent with certain embodiments of the present disclosure.

[0018] FIG. 7A shows an implementation of a recessed band electrode sub consistent with certain embodiments of the present disclosure.

[0019] FIG. 7B shows details of an electrode contact assembly in 7A consistent with certain embodiments of the present disclosure.

[0020] FIG. 7C is an end view of the recessed band electrode sub of FIG. 7A consistent with certain embodiments of the present disclosure.

[0021] FIG. 7D shows details of a near-bit transceiver element consistent with certain embodiments of the present disclosure.

[0022] FIG. 8 shows a block diagram of transceiver electronics for an electric field short range data link apparatus consistent with certain embodiments of the present disclosure.

[0023] FIG. 9 is a depiction of a cross-coil antenna consistent with certain embodiments of the present disclosure.

[0024] FIG. 10 depicts electric current lines consistent with certain embodiments of the present disclosure.

[0025] FIG. 11 depicts the placement of the cross-coil antenna consistent with certain embodiments of the present disclosure.

[0026] FIG. 12 depicts a multi-node bottom hole assembly communication consistent with certain embodiments of the present disclosure.

[0027] FIG. 13 is an isometric view of a wellpath with a 3-component magnetic sensor package and 3-component gravity sensor package consistent with certain embodiments of the present disclosure.

[0028] FIG. 14 is a detailed view of coordinate axes of the 3-component gravity sensor package, 3-component magnetic sensor package, and reference axes consistent with certain embodiments of the present disclosure.

[0029] FIG. 15 shows a schematic form of the magnetic field of a local source of magnetic variations along a wellbore.

[0030] FIG. 16 is a flow chart showing a process of locating the source of local magnetic variations along the wellbore by adjusting magnetic model parameters into agreement with measured magnetic deviations consistent with certain embodiments of the present disclosure.

[0031] FIG. 17A illustrates certain embodiments of the present disclosure used to reduce the influence of smearing.

[0032] FIG. 17B illustrates certain embodiments of the present disclosure used to reduce the influence of smearing, and shows a source of magnetic interference.

[0033] FIG. 18 illustrates a schematic illustration of a magnetic field measurement device in accordance with certain embodiments of the present disclosure.

DETAILED DESCRIPTION

[0034] It is to be understood that the following disclosure provides many different embodiments, or examples, for implementing different features of various embodiments. Specific examples of components and arrangements are described below to simplify the present disclosure. These are, of course, merely examples and are not intended to be limiting. In addition, the present disclosure may repeat reference numerals and/or letters in the various examples. This repetition is for the purpose of simplicity and clarity and does not in itself dictate a relationship between the various embodiments and/or configurations discussed. Moreover, the formation of a first feature over or on a second feature in the description that follows may include embodiments in which the first and second features are formed in direct contact, and may also include embodiments in which additional features may be formed interposing the first and second features, such that the first and second features may not be in direct contact.

[0035] The present disclosure relates generally to a measure-while-drilling apparatus used for directional drilling of boreholes in the Earth with an anti-collision system designed to provide real-time or near-real-time information relating to magnetic sources at or near a drill bit. In certain embodiments of the present disclosure, the anti-collision system includes a near-bit instrument package including a magnetic sensor, a measurement while drilling (MWD) system including an MWD transmission mechanism, and a short range communications system for transmission of data between the magnetic sensor and the MWD transmission mechanism. Non-limiting examples of MWD systems may include magnetometers and accelerometers, gyroscopes and accelerometers, or a combination of magnetometers, accelerometers and gyroscopes. In other embodiments of the present disclosure, a wired motor or a wireline may be used to transmit information between the magnetic sensors and the MWD transmission mechanism. An illustrative example of one embodiment of the present disclosure is shown in FIG. 2, described in detail below.

[0036] Directional drilling typically uses a bottom hole assembly (BHA) in a drill string, which typically includes a drill bit, stabilizers, bent subs, drill collars, and a rotary steerable system and/or a turbine motor (mud motor) that is used to turn the drill bit. Due to the mechanical complexity and the limited space in and around the BHA, the MWD system is typically placed some distance from the drill bit above a motor assembly. A communication link to the surface is typically established by the MWD system using one or more means, such as a wireline connection, mud pulse telemetry or electromagnetic wireless transmission. Because of the lag between the drill bit location and the magnetic sensors monitoring the progress of the drilling, the driller at the surface may not be immediately aware of an undesirable condition near the bit, such as an approach to a metallic object, for example, underground piping. For this reason, in certain embodiments the magnetic sensors and instrumentation used to determine an approach to a metallic object may be placed in the limited physical space in or below the motor assembly, and therefore closer to the drill bit, while maintaining a surface telemetry system above the motor assembly. These magnetic sensors generate near-bit data that is typically communicated to the MWD system to be transmitted to the surface.

[0037] FIG. 1 diagrammatically depicts a typical, non-limiting example of a rotary drilling installation of a type in which certain embodiments of the present disclosure may be used. The BHA includes drill bit 1 connected to a lower end of drill string 2, which is rotatably driven from the surface by rotary table 3 on drilling platform 4. A suitable drilling fluid, generally referred to as mud, may be pumped downward through an interior of drill string 2 to assist in drilling and to flush cuttings from the drilling operation back to the surface in annular space 2a outside of drill string 2. Rotary table 3 is driven by drive motor 5. Raising and lowering of drill string 2, and application of weight-on-bit, is under the control of draw works 6. Drill bit 1 may alternatively be rotated by a mud-motor contained within apparatus 7 that is located in drill string 2.

[0038] Apparatus 7 may include a traditional mud motor. In other embodiments of the present disclosure, apparatus 7 may be of the type described in U.S. Patent No. 8,069,716, Pahani, or U.S. Patent Application No. 11/820,790, VanSteenwyk, et al., which are incorporated fully herein by reference.

[0039] Mud Motors

[0040] FIGS. 3A through 3C depict a longitudinal cross section of a mud motor consistent with certain embodiments of the present disclosure. Main housing 11, which may include multiple sections along its length, has connection 12 at its upper end for connection to other elements of a drill string above the mud motor, indicated generally at 12a. While connection 12 is shown as a threaded connection, any suitable connection may be used. FIG. 3A further depicts stator 13 and rotor 14 for a "Moineau" or progressive-cavity type motor operated by the flow of drilling fluids pumped down through the drill string from the surface. Torsion bar or flexible shaft 16 is used to connect the eccentric motion of rotor 14 to lower elements 16a. Lower end of torsion bar or flexible shaft 16 is connected at 16b to rotary shaft 10, which drives drill bit 40 attached to the threaded connection 21 at the lower end of the mud motor. Bent subassembly 17 and case 18 house radial and thrust bearing assembly 19 that transfers load from drill bit 40 and rotary shaft 10, to case 18. Bending of the torsion bar or flexible shaft 16 accommodates both the eccentric motion of rotor 14 and the bend angle between main housing axis 41 of main housing 11 and bent axis 42 of the bent subassembly 17 and case 18. As shown, bent axis 42 is concave toward main housing axis 41, and convex radially away from bent axis 42. For suitable drilling operations the bend angle Δ between main housing axis 41 and bent axis 42 may lie in the range of 0 to 4 degrees.

[0041] In certain embodiments, the mud motor is manufactured from non-magnetic materials. In other embodiments, the mud motor is manufactured at least in part from non-magnetic materials. In still other embodiment, the mud motor is manufactured from magnetic materials.

[0042] In certain embodiments, sensor and data transmission assembly 15, adjacent case 18, may contain short range data transmission circuitry described below as a short range data communications system.

[0043] Drilling fluid enters the mud motor through the connection 12 and flows through interior fluid passage 22 and past torsion bar or flexible shaft 16, to exit the mud motor into drill bit 40 through connection 21. Because the sensor and data transmission assembly 15 is in parallel with and located at one side of the torsion bar or flexible shaft 16, there is no need for an axial opening through the sensor and data transmission assembly 15.

[0044] FIGS. 4A, 4B, 5, 5A, and 6 illustrate an alternative embodiment of a mud motor. The alternative embodiment includes housing 61, including first drive coupling 62 having upper end 64 that is attached to rotor 66, which is similar to rotor 14 shown in FIG. 3A. Lower end 68 of the first drive coupling 62 is attached to first end 70 of first driven rod 72. Second end 74 of the first driven rod 72 is attached to upper end 76 of second drive coupling 78, and lower end 80 of the second drive coupling 78 is attached to proximate end 82 of connecting shaft 84. Shaft bore 85 extends through connecting shaft 84. Top end 88 of third drive coupling 90 is attached to distal end 86 of connecting shaft 84, and bottom end 92 of the third drive coupling 90 is attached to upper portion 94 of second driven rod 96. Lower portion 98 of the second driven rod 96 is attached to upper end 100 of fourth drive coupling 102. Lower portion 104 of the fourth drive coupling 102 is attached to motor bearing section 106 and is connected to drill bit 108.

[0045] In operation, the connecting shaft 84 transmits rotational motion from the motor and the power generated by the motor through the offset bore to the drill bit 108. It is contemplated that the drive couplings, driven rods, and the connecting shaft 84 described herein can be attached by known latching mechanisms, such as a combination of pins and set screws. Other methods of attachment will be apparent to those of ordinary skill in the art. Recess 110 is disposed on housing 61 to accommodate sensor and data transmission assembly 116.

[0046] Bore 112 of the housing 61 is an eccentric bore that is offset from the main housing axis 114 of the housing 61. A suitable offset from the main housing axis 114 may be selected for any given design of the mud motor. For example, in one embodiment, the offset is approximately 0.35 inches. Other offset distances may be selected without departing from the spirit of the present disclosure. The offset configuration allows the bore 112 to accommodate the sensor and data transmission assembly 116 on the housing 61. One of ordinary skill in the art will appreciate that the bore offset may be varied to suit design requirements.

[0047] First and second radial bearings 120a and 120b are disposed in the housing 61 to support the connecting shaft 84. The first and second radial bearings 120a and 120b prevent the connecting shaft 84 from rubbing against inner surface 122 of the housing 61. This arrangement of the connecting shaft 84 and the first and second radial bearings 120a and 120b protects the inner surface 122 of the housing 61 from wear and tear, and prolongs the service life of the mud motor.

[0048] The bent housing 109 defining a bend angle α is disposed between the housing 61 and the drill bit 108 to enable an operator to change the trajectory of the drill bit 108 where directional drilling is desired. The embodiment of FIG. 4A. is capable of achieving directional drilling because each coupling between the connecting shaft 84, the drive couplings 62, 78, 90, 102, and the driven rods 72, 96 are capable of about a 6 degree bend, as will be evident to one of ordinary skill in the art. The connecting shaft 84 is also able to accommodate the eccentric motion of the rotor because of the flexibility in the couplings.

[0049] Bottom Hole Assembly

[0050] FIG. 2 is schematic representation of a BHA consistent with certain embodiments of the present disclosure. BHA 800 includes, as either a separate sonde or built integrally within drill collars, MWD system 801, a formation resistivity sensor 802, rotary steerable device or mud motor 803 and near-bit magnetic sensors 804. Sensors other than the magnetic sensors 804 may be located near drill bit 806 as well, including a natural gamma ray sensor, inclinometer or other sensors used in logging or geo-steering of boreholes. In certain embodiments of the present disclosure, the magnetic sensors 804 are located in a separate, non-magnetic carrier sub assembly. The magnetic sensors may be located within 12 feet of drill bit 806, within 10 feet of drill bit 806, within 8 feet of drill bit 806, within 5 feet of drill bit 806, within 1 foot of drill bit 806 or adjacent to drill bit 806.

[0051] FIG. 2 also depicts a short range communications system consistent with the short range data transmission system described by U.S. Patent No. 7,518,528. Four uses of insulated electrodes 805 are shown in FIG. 2, which provide the means for injecting electrical current into the drilling fluid and the Earth formation, as well as providing the means for receiving a current injected by any one of the other communication nodes in the system. Such electrodes have their outer surfaces at or adjacent the drill string outer surface 810. Data communicated between these nodes can be transmitted to the surface by MWD system 801 for analysis. This is a non-limiting embodiment and other forms of short range transmission systems are described herein.

[0052] Short Range Transmission Systems

[0053] Data generated by the near-bit magnetic sensors may be transmitted uphole. In certain embodiments of the present disclosure, a short range data communications system may be used. Short range data communications systems include, but are not limited to, the Short range data transmission systems described in US Patent No. 7,518,528, Price et al., U.S. Patent No. 8,258,976, and US. Application No. 13/572,338, Graf et al., US Patent No. 5, 160,925, Daily et al., which are fully incorporated herein by reference. In other embodiments, a short range acoustic data transmission system may be used, such as that described in US Patent No. 5,924,499, Birchak et al., which is fully incorporated herein by reference. In still other embodiments, downhole mud-pulse may be used wherein communication between down-hole positions is performed via mud-pulse. In yet other embodiments, magnetic field communication between down-hole positions may be accomplished through axially or laterally wound coils, such as solenoids, such as is described by U.S. Patent No. 8,242,929, which is incorporated herein by reference.

[0054] FIG. 7 depicts one embodiment of a short range communications system 500 including insulated band recessed conductive electrode 535 on near-bit sub 530 below bit rotating mud motor 540 or other mechanical means 550, as well as insulating gap type electrode 570 on sub

401 above the mud motor 540 or other mechanical means 550. The insulating gap type electrode 570 can serve as both an upper electrical contact for the short range communications system and as a lower terminus of a surface link. In another embodiment shown in Fig. 7A, the insulated gap type electrode 570 is replaced by a mud pulser, not shown, and upper sub 560. In this embodiment, recessed, insulated conductor type electrodes at both ends of a short hop link are used, including insulated band recessed conductive electrode 535 near the drill bit and insulated band recessed conductive electrode 1020 (FIG. 7A) near the mud pulser and above a motor or other physically obstructive mechanical means. Band type, recessed, insulated electrodes are shown for illustrative purposes, although other shapes of recessed, conductive electrodes may be used. Insulated band recessed conductive electrode 535 and its associated short-range data transmission receiver (transceiver) may be in wired communication with a mud pulser control sub contained in an elongated housing of upper sub 560, as shown in FIG. 7.

[0055] One embodiment of the present disclosure, referring to FIG. 7 and to FIG. 7D, includes near-bit sub 530 (FIG. 7) or 600 (FIG. 7D) containing a power source, drilling environment sensors, a memory circuit and communication management controller, and a transmitter and receiver, all housed in space 630 and electrically connected to cylindrical, metal band electrode 610, which is received in solid dielectric-filled groove 620 in the outer wall of the near-bit sub 530 or 600. The metal band electrode 610 is exposed to be in electrical contact with surrounding drilling mud 409 in wellbore 410, and communicates by driving an AC, data-modulated current into the surrounding drilling mud 409 and, in some embodiments, into formation 411. This AC, data-modulated current is received by uphole insulated gap type electrode, or electrodes, 570, is demodulated, and is stored in memory circuitry contained in space 559 in sub upper 560 in preparation for transmission by an associated electric conduction surface link. A return short range transmission data link functions similarly, but uphole insulated gap type electrodes 570 may transmit interrogation or control-format data to the lower, near-bit sub, 530 or 600.

[0056] The short range transmission data link may have data rates in the 10 to 50,000 baud range. Link carrier frequencies may be in the 100 to 100,000 Hz range. Both recessed conductive and gap electrode types involved are broad band relative to this range. A plurality of codes and frequencies are typically used, depending on the link function and local conditions. Codes can be, but are not limited to, Frequency Shift Keying (FSK), Pulse Width Modulation (PWM), Pulse Position Modulation (PPM), Frequency Modulation (FM) and Phase Modulation (PM), Pulse

Code Modulation (PCM), Chirp Spread Spectrum (CSS), Direct Sequence Spread Spectrum (DSSS), Frequency Hopping Spread Spectrum (FHSS) and Trellis Coded Modulation (TCM). Single and multiple simultaneous carrier frequencies may be used, both within and outside of the expected frequency range. Electric field transmission in both mud and the formation may be utilized.

[0057] In other embodiments, the same or overlapping bandwidth may be used for each access point for the short range transmission system. Such methodologies may increase effective data rate transmission by reducing or eliminating the need to sequentially query each of the short hop transmission points. Techniques for such methodologies include, but are not limited to, Code Division Multiple Access (CDMA), Orthogonal Frequency Division Multiple Access (OFDMA), and Single Carrier Frequency Division Multiple Access (SC-FDMA).

[0058] Lower near-bit sub 530 or 600 receiver can be commanded by circuitry at upper sub 560 (FIG. 7) to modify its data collection, memory use, transmission schedules and other functions. Upper sub 560 may be in contact with other nearby sensor tools, and may contain or be in contact with management and control electronics sufficient to constitute an MWD system. Referring to FIG. 7, upper sub 560 uphole, above mud motor 540 and other mechanical means 550, such as other collars and subs, may contain the sensors, power supplies, control processor and electronics, not shown, that are required to both communicate upwardly with surface equipment and downwardly with the near-bit sub 530 or 600, with the end objective of collecting and communicating the most useful drilling condition data to the surface in a timely fashion. In certain embodiments, upper sub 560 contains a two-way electric field direct conduction means used to communicate with the surface.

[0059] FIG. 7 also shows the general arrangement of one embodiment of the present disclosure, a pure conduction datalink between the insulated band recessed conductive electrode 535 on the near-bit sub 530 and the insulating gap type electrode 570above the mud motor 540 and mechanical means 550. Short range communications system 500 may consist of a drill bit 510, bit box 520, near-bit sub 530, mud motor 540, mechanical means 550 that may include a mud pulser and an MWD sensor, and upper sub 560, which may be an electric field surface conduction transmitter/control sub below the insulating gap type electrode 570 in the drill string.

[0060] Referring to both FIG. 7 and FIG. 7D, the near-bit sub 600 may contain drilling environment sensors and a transceiver, in space 630, for both sending their outputs to the upper sub 560 transceiver, and for receiving commands from that transceiver. Upper sub 560 may be in wired communication with the surface link transceiver sub, also in upper 560, and may submit its own sensor output data to it. The upper sub 560 contains storage and control processors that are in two-way communication with surface operators, via the gap-to-surface transceivers that provide the upwards and downwardly communication in the upper sub 560. Both near-bit and upper short hop subs may contain power sources, control, memory and communication management functionalities, not shown.

[0061] In the another embodiment, upper sub 560 and associated insulating gap type electrode 570 are replaced with a similar sub shown in FIG. 7A, which is detailed in FIG. 7B. A insulated band recessed conductive electrode 1020, as referred to above, is in two-way communication with the near-bit sub 530 or 600, and uses a mud pulser, not shown, in place of insulating gap type electrode 570 for communication to or with equipment at the well surface.

[0062] In the embodiment shown in FIG. 7, the insulated band recessed conductive electrode 535, insulated from the short range communications system 500 body, injects modulated currents into the mud and formation, and most of such currents return nearby to the short range communications system 500 body. A fraction of the injected currents--"a" in FIG. 7—return to the uphole body above the insulating gap type electrode 570. These datalink signals produce a voltage across the gap on their way back to downhole short range communications system 500, and are received, demodulated and stored as near-bit sensor output data. The dashed lines in FIG. 7 represent conduction current paths, as in the formation, assuming the insulated band recessed conductive electrode 535is transmitting and the gap is receiving. A similar reciprocal current pattern is generated when the insulating gap type electrode 570 transmits and the insulated band recessed conductive electrode 535receives, with the highest current density centered on the gap, and a small fraction being intercepted by the insulated band recessed conductive electrode 535 as command signal currents on their way to the sub body underneath the insulated band recessed conductive electrode 535. Because the gap conductive uphole and downhole electrodes are axially much longer than the insulated band recessed conductive electrode 535, they have a greater current collecting and emitting area, which tends to compensate for the lower "gain" of the compact near-bit band end of the link.

[0063] In another embodiment, where the insulating gap type electrode is replaced by another insulated band recessed conductive electrode 1020 (FIG. 7A), communication is similar to the above description. The insulated band recessed conductive electrode 1020 can be made axially longer than the near-bit insulated band recessed conductive electrode 535 to provide more current contact area and link margin, if required.

[0064] FIG. 7 shows details of one example of a near-bit transceiver sub, near-bit sub 600, common to several embodiments. The sub body may be made of steel, with threads 640 and 645 to mate with the bit box and mud motor drive shaft, respectively. The near-bit sub 600 may be cylindrical in cross section, and may be of larger diameter than adjacent components, for both strength and electronics/battery volume reasons. The near-bit sub 600 has a central circular through channel 650 for drilling mud flow, with appropriate seals. The near-bit sub 600 interior includes chambers with appropriate seals for electronics and batteries, such as space 630, and for sensor ports 660. Sealed, removable plug 670 may provide access to a power-on switch. The sensors themselves and their support electronics are mounted in zones or cavities, such as space 630. Sensor support may include control, sensor activation and data memory, all linked to the uphole MWD/surface conductive subs via an internal transceiver. This transceiver may be connected to metal band electrode 610, which is edgewise supported mechanically by an insulation layer, such as solid dielectric-filled groove 620. The metal band electrode 610 may in one non-limiting embodiment be made from titanium, and the insulation in one non-limiting embodiment may consist of polyetheretherketone (PEEK) or another rugged, vacuum setting epoxy or polymer. Not shown are appropriate electrical leads and pressure-tight fittings connecting the electronics chambers to the electrode and sensor ports. In an alternate implementation, the near-bit sub 600 may contain only the electronics payload, with the batteries contained in a separate, removable adjacent sealed sub. In other embodiments, power may be provided from the surface, or generated downhole. Downhole methods include, but are not limited to, mud turbine alternator or via energy scavenging from vibration. The disclosure is not limited to the method of power delivery or generation.

[0065] While a circumferential metal band electrode 610 is shown for illustrative purposes, a number of other geometries are also useful for implementing conduction link electrodes. These include arrays of recessed bands spaced apart axially on the near-bit sub 600, separated from each other by dielectric strips. If selectively connectable to a single, or multiple transmitters, these would allow matching electrode drive point impedance to transmitter capabilities in varying mud salinities. Also included are strips, rectangles and other symmetric and asymmetric geometric shape electrodes that are tailored to optimally utilize the surface area available on a sub or other host carrier. These also may be arrayed and driven selectively to match impedance, similarly to the bands.

[0066] For a mud pulser surface link embodiment, FIG. 7A shows an implementation of an upper band electrode mounted on the surface link sub. This electrode may be used for one- or two-way communication with the lower sub of the short hop link. Referring to FIG. 7A, the insulated band recessed conductive electrode 1020 is mounted in an insulating bed 1030, and is electrically connected to a removable electronics interface 1010. The removable electronics interface 1010 may have standard threaded and connector ends and may be designed to accept a mud pulser or other surface communication means on one side, with sensor and control tools on the other side. The removable electronics interface 1010 may consist of a central pressure barrel 1010a and an outer annular sleeve 1010b supported by three vanes, which allow drilling mud to flow through assembly gaps 1010c. The outer annular sleeve 1010b may be held against a shoulder of its host sub by the weight of the attached tool string and by a threaded pin 1040, which also fixes its rotational position. Referring to FIG. 7B, the metal band electrode has a metal contact pin 1060 threaded into it. The smooth lower portion of the metal contact pin 1060 may be enclosed by an insulating cylinder 1050. The inside ends of the metal contact pin 1060 and insulating cylinder 1050 are made flush with interior wall 529 of the host upper sub 560. The outer annular sleeve and thick vane of the removable electronics interface 1010 support a sliding, spring-loaded electrical contact assembly 1070. The sliding, spring-loaded electrical contact assembly 1070 may consist of a cylindrical insulating block on which is mounted a thin, rounded, spring steel contact 528 pressed against the interior wall 529of the upper sub 560 by a coil spring. The contact presses against the end of the threaded pin 1040 when assembled, making electrical connection to the band electrode. Insulated wire 1090 connects the spring steel contact to the transceiver inside the central pressure barrel tool string. In the embodiment shown, the insulated wire 1090 passes through a cylindrical pressure seal channel before entering barrel 527. Double or quadruple "O"-ring seals 1080 in the outer annular sleeve seal the sliding contact against drilling mud 526. High temperature silicone cement offers one non-limiting way to form pressure seals in the wire channel, and between the insulating cylinder 1050, metal contact pin 1060 and the interior wall 529.

[0067] FIG. 8 shows a block diagram of the electronics for one embodiment of a short range communications system. Near-bit sub 700 may contain a primary power source, sensors, control, signal processing and storage, and a short-range communication transceiver. In certain alternate embodiments, the transceiver may only be a transmitter. In some embodiments, the short range communications system includes only a short hop transmitter and an MWD short hop receiver in electrical communication with a surface transmitter. Uphole end of the short range link 737 may consist of a transceiver sub and an MWD sub, in wire communication. The transceiver sub can in the first, preferred embodiment, maintain two-way communication with both surface operators and with the near-bit sub, using one gap-type transmit/receive electrode pair. This sub, in general, contains downhole and uphole transceivers, a surface-reprogrammable system controller and sensor data collection/transmission/interrogation management function, storage and primary power. The surface and short-range links may be different in frequency, power and modulation formats. The surface transceiver may also be used to communicate with the near-bit sub, either with the same or different signals it uses to communicate with the surface. The MWD sub may contain sensors, signal processing, storage and primary power. In another, alternate embodiment, the electric field two-way surface link, not shown, is replaced with an uphole direction only mud pulser, not shown. The transceiver sub may then perform as the autonomous, pre-programmed system controller, independent of the surface. The transceiver sub short-range transceiver may then be connected to an adjacent recessed band conduction electrode sub, such as upper sub 560 shown in FIG. 7A, and its surface transceiver is replaced with a mud pulser controller resident in its system controller 745 module in FIG. 8. In this embodiment, the near-bit sub may be controlled by the associated system controller 745, or, by the nearby MWD system control 755 in that sub, which may be in wire communication with the surface link sub.

[0068] Referring to FIG. 8, the near-bit sub 700 can include a transceiver 710 having its own system controller and communications management 715, sensors 720, sensor data processor 725, data and command storage media 730 and local primary power 735. The near-bit sub 700 may be interrogated by either system controller 745 or MWD system control 755 via the short hop link. In the uphole end of the short range link 737, of the short range link, the MWD sub includes the MWD system control 755, sensors 770, associated sensor data processing 760, and data storage 765. The MWD sub may be in wire communication with the transceiver sub, comprising transceiver 740, system controller 745 and storage 750. Both sets of subs may be dependent on their own primary power supplies 775. Depending on which implementation of the surface link is present, either gap or mud pulser, control programming, functions and transceiver 740 communication frequencies and protocols will be changed appropriately.

[0069] It is contemplated that other, simpler, alternate implementations exist, wherein all communication is unidirectional only. In the uphole only case, the near-bit sub transceiver 710 reverts to a transmitter and the uphole transceiver 740 reverts to only a short-range link receiver. System controller 745 may then send near-bit and MWD sensor data to the surface via mud pulser.

[0070] In still another embodiment, FIG. 9 is a depiction of a cross-coil antenna consistent with certain embodiments of the present disclosure. A section of drill string 2 is shown with drill string collar 1100. Drill string 2 has drill string axis 1102. Cross-coil antenna 1104 is shown within drill collar cutout 1106.

[0071] Cross-coil antenna 1104, as shown in FIG. 9, is rectangular, with cross-coil sides 1110 being longer than cross-coil cross sides 1112. Cross-coil antenna 1104 may have multiple windings 1108. The longer side of cross-coil windings 1108 may run essentially parallel with drill string axis 1102. The number of windings may be between 1 and 300, alternatively between 5 and 75, or between 10 and 40. In other embodiments of the present disclosure, cross-coil antenna geometries can include, but are not limited to, circles, ovoids, squares, and other polygons. When the cross-coil antenna 1104 is rectangular, as depicted in FIG. 9, the cross-coil sides 1110 may be considerably longer than that the cross-coil cross sides 1112. In certain non-limiting embodiments, the ratio of cross-coil side length to cross-coil cross side length can range from 1:1 to 1000:1, from 10:1 to 100:1 or from 20:1 to 200:1. When the cross-coil side length exceeds that of the cross-coil cross side length, the cross-coil antenna 1104 is an elongated rectangle. The elongated rectangle form allows the cross-coil antenna 1104 to have a larger area while in place within the drill collar cutout 1106 than if the cross-coil side length was less than or equal to that the cross-coil cross side length. The cross coil sides 1110 may run essentially parallel with longitudinal drill string axis 1102. The cross-coil cross sides 1112 may be essentially perpendicular to the cross-coil sides 1110. "Essentially perpendicular" allows orientation of the cross-coil cross sides 1112 to be rotated about the cross-coil sides 1110 by as much as about 50°.

[0072] In certain embodiments, the cross-coil antenna 1104 may have a ferrite or ferromagnetic core. When the cross-coil antenna 1104 has a ferrite or ferromagnetic core it may be desirable to cover the core with protective insulating material along the entire length of the cross-coil antenna 1104 in order to prevent the ingress of mud and water and to prevent mechanical damage. The type of insulating material is not critical and any suitable material may be used. In other embodiments, the cross-coil antenna 1104 may have an insulating material as a core. In those embodiments, the resistivity may be more than 10 Ohm□m, 100 Ohm□m, 1000 Ohm□m or 1015 Ohm□m.

[0073] The cross-coil antenna 1104 is electrically connected to a voltage source (not shown) sufficient to impart a current to the cross-coil antenna 1104, generating a magnetic field. When an alternating voltage source is activated, the cross-coil antenna 1104 forms a magnetic field which is capable of inducing a current in the drill string 2. In some embodiments, the frequency range of the excitation of the cross-coil antenna 1104 is from 10 Hz to 100 kHz, from 100 Hz to 10 kHz or from 400 Hz to 4 kHz. Without wishing to be bound by theory, an alternating magnetic field is created by an alternating current (AC) signal made to flow through an appropriate inductor, typically a coil of wire mounted on or around the drill pipe, thereby creating a magnetic flux. The presence of a highly permeable material, such as ferrite or ferromagnetic material, has the effect of increasing the effective area of the inductor, and correspondingly increasing the magnetic flux. Lines of flux are thus concentrated by the ferrite or ferromagnetic material, which acts as a conduit for the alternating magnetic field.

[0074] The cross-coil antenna 1104 is also capable of detecting an alternating current on the drill string 2. An AC current on the drill string 2 creates an alternating magnetic field in the cross-coil antenna 1104 that induces a voltage across the cross-coil antenna 1104 ends. In certain embodiments of the present disclosure, one end of the cross-coil antenna 1104 may be connected to the drill string 2 or the sensor package.

[0075] FIG. 10 depicts the current flow lines 1200 generated by certain embodiments of the present disclosure. When the voltage source is activated, the cross-coil antenna 1104 generates a magnetic field and thus is inducing a current through the drill string 2 having the drill bit 1, and through the formation.

[0076] The cross-coil antenna 1104 may transmit signals to a gap electrode, a band electrode, a toroidal antenna, or to another cross-coil antenna. Examples of gap electrodes and band electrodes are discussed above. An example of a toroid antenna may be found in U.S. Patent Application No. 5,160,925, which is fully incorporated herein by reference.

[0077] FIG. 11 depicts a particular embodiment of the present disclosure with the current flow lines 1200 shown. Lower downhole assembly 1500 includes drill bit 1510, bit box 1520, near-bit sub 1530, mud motor 1540, a string of subs and collars 1550 that may include a mud pulser, an MWD sensor, and electric field transmitter to surface with its control subs 1560 below an insulated gap type electrode 1570 in drill string 2.

[0078] The cross-coil antenna 1104 is further depicted in FIG. 11 on near-bit sub 1530 at a lower location below the mud motor 1540 or string of subs and collars 1550 and an insulating gap type electrode 1570 on sub 1401. In the embodiment depicted in FIG. 11, the insulating gap type electrode 1570 can serve as both the upper electrical contact for the short hop communication link of one embodiment of the present disclosure and as the lower terminus of a surface link. In an alternative embodiment, a surface communication link can be accomplished by mud pulse type. In this alternative embodiment, the insulated gap type electrode 1570 may be accompanied by a mud pulser, not shown. The upper electrical contact for the short hop communication link could also be a toroidal antenna, a band electrode, or another cross-coil antenna.

[0079] In certain embodiments, in particular when oil-based-mud is in use, a cross-coil antenna may be used as a transmitter, with the receiver being a toroid antenna, insulating gap type electrode, or another cross-coil antenna.

[0080] In another embodiment, a cross-coil antenna may be used as part of a multipoint communication network in the bottom hole assembly and drill string 2, wherein a transceiver for each node in the system is utilized. FIG. 12 schematically shows one such multipoint communication network. Numeral 1800 designates the bottom hole assembly of the drilling assembly. Mounted within the bottom hole assembly 1800 as a sonde, or built integrally into the drill collars, are an MWD system 1801 and a formation resistivity sensor 1802. Numeral 1803 depicts a rotary steerable device and numeral 1804 shows a near-bit sensor located just above the drill bit 1806. The near-bit sensor 1804 may include devices such as a natural gamma ray sensor, inclinometer or other sensors used in logging or geosteering of boreholes. Four uses of the cross-coil antennas 1104 are shown. Data communicated between these nodes can be used by the rotary steerable device 1803 to adjust the course of the drilling or can be transmitted to the surface by the MWD system 1801 for analysis by the directional driller; thereby enabling wireless means for these independent sensors to share information and use that information to change events in the process of drilling a borehole. In other embodiments, one or more of the cross-coil antennas 1104 may be replaced with a toroid antenna, insulating gap type electrode, or band electrode.

[0081] Magnetic Sensor Compensation

[0082] In certain embodiments of the present disclosure, data generated by the near bit magnetic sensors may be affected by the proximity of the magnetic sensors to the drilling mechanism, including the drill bit itself. In these embodiments, compensation of the effect of the drilling mechanism on the data generated by the magnetic sensors may be performed, such as within electronic equipment located within a carrier sub assembly with the magnetic sensors, an up hole navigation system, or on the surface.

[0083] One non-limiting example of how compensation of the magnetic sensor data may be accomplished is through the use of magnetic navigation sensors in use with the MWD system. In these embodiments, a set of correlated clocks are located within both the MWD system and the near bit sensor package. At pre-determined intervals, the MWD navigation sensors and near bit sensors are sampled. Software located at the surface, or firmware located within the MWD system or the near bit sensor package, establishes a reference coordinate system for each set of sensors. Acceleration sensors of the MWD navigation system and of the near bit sensor package may be used to rotate the sensor coordinate system of the data from the near bit sensors to match the MWD navigation sensor set. This action will correct for such effects as collar windup and BHA sag, *i.e.*, misalignment of directional sensors with the borehole direction due to deflection of the MWD drill collar under gravity and borehole curvature. The data from the magnetic sensors in the near bit sensor package may then be compared to that of the MWD navigation sensors. The firmware or software may then compensate the rotated data from the near bit magnetic sensors and rotate the data back to the near bit sensor package coordinate system. In other embodiments, rather than rotating the near bit sensor package coordinate system, the reference coordinate system is rotated to match the near bit sensor package coordinate system.

[0084] One non-limiting example of magnetic sensors is described in US Patent No. 5,960,370, Towle et al., which is incorporated fully herein by reference. In certain embodiments of the present disclosure, anti-collision data may be provided by the system described in US Patent No. 5,960,370. In these embodiments, distance and direction to the magnetic source may be calculated, allowing an operator to determine the location of the magnetic source. Further, because of the proximity of the magnetic sensors to the drill bit, the determination of the location of the magnetic source may be determined earlier than if those same sensors were located further up the drill string, for example, nearer the MWD system.

[0085] Downhole Magnetic Measurement

[0086] In certain embodiments of the present disclosure, the magnetic sensors include a triaxial vector magnetometer. In these embodiments, the magnetic sensors may identify the magnetic field of a nearby magnetic object of magnetic source for subsequent analysis or determination of the position and attitude of the magnetic object. Vector magnetic field measurements may be taken at intervals along a wellpath, and, by use of a mathematical function having parameters to represent the azimuth and changes along the wellpath, an approximation to the Earth's magnetic field vector, as measured by the 3-component borehole magnetometer along the wellpath, may be determined. The parameters of this mathematical approximation may be adjusted to fit lower order variations of the measured magnetic field vector, such lower order variations being caused by changes in the wellbore azimuth. In these embodiments, the position and angular attitudes of a sub-surface source of magnetic field disturbance relative to the sub-surface curved path of a wellbore may be determined by:

[0087] a) obtaining a determined magnetic field of the source from measurements of total magnetic field at locations along the path,

[0088] b) providing an adjustable parametric model of the source wherein the source magnetic field position and attitude are a function of the position and attitude parameters of the source,

[0089] c) deriving from the parametric model an estimate of the magnetic field of the source,

[0090] d) comparing the determined magnetic field of the source with the estimate of the magnetic field of the source to produce a difference value or values, and

[0091] e) adjusting the parametric model position and attitude parameters to minimize the difference value or values.

[0092] FIG. 13 shows a wellpath or wireline 1201 described by its inclination and azimuth with respect to an external North (N), East (E), and downwards (D) on a rectangular coordinate system 1202 at a series of locations or points 1203, 1204 and1205 along the wellpath or wireline 1201. The bore is identified as numeral 1300. An instrument housing 1206 can be attached to the wellpath or wireline 1201.

[0093] FIG. 14 depicts the instrument housing 1206 attached to a wireline carrying a triaxial vector magnetometer sensor package 1207. In certain embodiments of the present disclosure, the triaxial vector magnetometer sensor package 1207 includes fluxgate or solid state type magnetic sensors. In certain embodiments, the triaxial magnetometers are of the manetostrictive or magnetoinductive types. The instrument housing 1206 also includes sensors and electronics for measuring the local direction of gravity 1208, for example, with respect to the wellbore direction. The instrument housing 1206 traverses the wellpath along its length, making measurements of the vector magnetic field and gravity vector at a series of points along wellpath. The instrument housing 1206 may be fixed to the bottom hole assembly of the drill string or attached to wireline in an open hole. Instrumentation of this general type is disclosed in U.S. Pat. Nos. 5,398,421, 5,564,193, 5,452,518, and 5,435,069, and references cited therein. U.S. Pat. Nos. 5,398,421, 5,564,193, 5,452,518 and 5,435,069 are incorporated fully herein, by reference.

[0094] Measurements along the 3-component axes of the triaxial vector magnetometer sensor package 1207 at each measurement point are resolved using gravity vector 1209 measured on or along 3-perpendicular axes 1210, 1211 and 1212 of the rectangular coordinate system 1202 to determine tool inclination and rotation about the tool axis. An Euler rotational transformation may be used to convert the measurements on the magnetic sensor axes 1213, 1214 and 1215 to equivalent values in a rectangular coordinate system having one horizontal component 1216 in the direction of the wellpath at the measurement point, a second horizontal component 1217 perpendicular to the wellpath direction, and a downward (vertical) component 1218. Circuitry within the triaxial vector magnetic sensor package 1207 may be used to provide the Euler rotational transformation. The components 1216, 1217 and 1218 are magnetic components.

[0095] Equation 1, set forth below, is consistent with one embodiment of the present disclosure. In this embodiment, Earth magnetic field vector Bx in the horizontal plane (N,E in FIGS. 13 and 14) is represented by an estimate of the horizontal Earth field magnitude, H, and by a third order function of distance along the wellpath, az(md);

[0096] $$Bx=H*cos(az(md)) \quad (1)$$

[0097] and similarly, the Earth magnetic vector By in the horizontal plane (where vector By is normal to vector Bx) is represented by the expression:

[0098] $$By=H*sin(az(md)) \quad (2)$$

[0099] where

[00100] $az(md)=a0+a1*(md-md0)+a2*(md-md0)^2$ (3)

[00101] In this embodiment, the parameters H, a0, a1, and a2 are or may be adjusted to cause the calculated quantities to match the horizontal components X, Y in a least-squares sense, such that the value

[00102] $F=sum((X-Bx)^2-((Y-By)^2))$ (4)

[00103] is minimized. The indication "sum" indicates the summation over a set of measurements along the wellbore. The resulting vector magnetic field estimate (Bx,By) then approximates the Earth field vector along the wellpath. Parameter md0 is a reference depth along the wellpath.

[00104] While the horizontal components of the magnetic field are often large, the presence of a magnetic disturbance may be observed directly in the field vertical component. Upon applying the algorithm described above, an approximation to the earth magnetic field vector along the measurement path in the wellbore may be obtained, and upon subtraction of the earth magnetic field vector from the total magnetic field vector along the wellbore, the resultant magnetic field vector of the disturbance at various locations along the wellbore is obtained.

[00105] Having determined the vector magnetic field of the disturbance along the wellpath, such as the method described above, the location of the source of magnetic field disturbance may be determined. FIG. 15 shows the relationship between the wellpath 1227 and the source of magnetic field variations. The source of magnetic variations may, for instance, be a connected series of well casing segments 1228, 1229, 1230 and 1231 defining the wellpath or borehole having magnetic field lines 1299. Non-magnetic drill collar 1232 and instrument housing 1233 are suspended in the pipe string.

[00106] FIG. 16 depicts a method of determining the position and attitude of a source of magnetic field disturbance. The vector magnetic field 2116 of the target object along the wellpath is determined by subtracting the Earth field components 2117 along the wellpath from the measured field 2118 along the wellpath. The resultant vector magnetic field 2116 of the target object is then compared at comparator 2122 with the model field 2120 produced by a parametric model 2125, with the parameters 2125a and 2125b of the model adjusted, as represented at 2121, until a suitable agreement is achieved. Such agreement may be made by visual observations. The position and attitude of the target, as seen at 2123, are then known from the known parameters of the model 2125. FIG. 16 may be regarded as a circuitry functional block diagram.

[00107] Another aspect of the present disclosure permits reduction of errors in estimated source position, caused by the effect known as "smearing". This term refers to the effect on the magnetic fields of a monopole pair, which exist on a magnetized iron object caused by the magnetic permeability of the iron itself. The magnetic field of an iron object, magnetized along its long axis, is approximately described by monopoles for the purposes of estimating range and attitude, such monopoles located a short distance from the extremities of the object. The actual field is the field of this monopole pair modified by the iron object itself, which typically provides a low permeability path for a portion of the magnetic flux caused by the remnant magnetization of the object. The phenomena of smearing are represented in FIGS. 17A and 17B.

[00108] In the aspect of the present disclosure shown in FIG. 17A, the magnetic field vectors of an ideal pair of monopoles 1225 and 1226 caused by the remnant magnetization of the object, i.e., target, in the steel wall casing section 1224 are shown as they would exist without smearing. The summation of the fields from each monopole results in the total field 1223 of the casing. The casing is shown in broken lines representing the absence of smearing.

[00109] In FIG. 17B, the effect of the casing permeability is shown. A portion 1221 of the magnetic field of the monopoles, parallel to the casing, is shown on the casing, resulting in a reduced axial field 1219 external to the casing. The effect is to cause an error in the estimate of distance to the casing if a simple model comprising only the field of the two monopoles is used.

[00110] In certain embodiments of the present disclosure, a well is drilled, such as in FIG. 15, to within close proximity and approximately parallel to the source of magnetic disturbance, in this case, an adjacent wellbore lined with segments 1228, 1229, 1230 and 1231 of wellbore casing. Also see the casing section 1224 in FIG. 7B. Because the transverse (cross-axis) component 1235 of the field of the casing is less affected by its permeability, the cross-axis field can be used to estimate the range to the target with less error caused by smearing.

[00111] Downhole magnetic measurement while rotating

[00112] In certain embodiments of the present disclosure, magnets may be used that are capable of being used during drilling. In these embodiments, a triaxial vector magnetometer is provided and affixed to a drill string subassembly. The triaxial vector magnetometer is adapted to measure three orthogonal magnetic field components. While the drill string subassembly is rotating, as during drilling operations, an average total magnetic field value (B_{TwR}) is determined as an average of the instantaneous vector magnitudes of the three orthogonal magnetic field components. In this way, near-bit estimates of the downhole magnetic field may be determined.

Magnetic Field Determinations

[00113] FIG. 18 illustrates a schematic illustration of a magnetic field measurement device 2150 in accordance with certain embodiments of the present invention. FIG. 18 shows one possible implementation of the magnetic field instrument device 2150. A person of ordinary skill with the benefit of this disclosure would recognize that many of the individual components shown in FIG. 18 are optional.

[00114] Triaxial vector magnetometer 2210 is adapted to measure three orthogonal magnetic field components. In this embodiment, triaxial vector magnetometer 2210 houses three separate vector magnetometers 2211, 2212 and 2213. In certain embodiments, vector magnetometers 2211, 2212 and 2213 may be integrated into one single sensor. Accordingly, as used herein, the term "triaxial vector magnetometer" refers to triaxial component magnetometers composed of a plurality of independent sensors and triaxial magnetometers wherein the triaxial component measurement functions are integrated into a single sensor.

[00115] Accelerometers 2201, 2202 and 2203 provide additional measurement data, which may be used by the methods as needed, as provided below. In some cases, one or more of the accelerometers may be an inclinometer.

[00116] Sensor outputs 2207, 2208, 2209, 2217, 2218 and 2219 are then transmitted to filter and gain processing unit 2220 to provide optional filtering and/or signal gain as desired. It is recognized that the processing provided by filter and gain processing unit 2220 may be accomplished by digital circuitry, such as by a microprocessor or analog circuitry. Accordingly, in this context, the term processing does not necessarily imply the presence of a processor. Optional oscillator 2261 drives fluxgate or solid state clock 2263, which is in turn used by the fluxgate or solid state magnetometers.

[00117] Multiplexer 2230, analog to digital converter 2233 and latching unit 2235, along with microprocessor 2250, combine to provide processing of sensor outputs 2217, 2218 and 2219. Control bus 2242 and data bus 2244 provide interconnectivity and functionality for communication among, and functioning of the various components shown herein. The particular exact hardware implementation shown here is only one possible implementation and the processing described herein may be accomplished through a variety of hardware implementations as would be recognized by a person of ordinary skill with the benefit of this disclosure. More specifically, microprocessor 2250, which is powered by power source 2249, determines the average total magnetic field value (B_{TwR}) from sensor outputs 2217, 2218 and 2219.

[00118] Another possible alternative implementation would be to incorporate a simultaneous sampling analog-to-digital converter that would sample each of the B_x, B_y and B_z inputs simultaneously rather than in sequence as is shown in the implementation depicted in FIG. 18 with the MUX and single A/D hardware. The advantage of this alternative technique is a removal of the error caused by the samples of B_x, B_y and B_z being taken at different points in time. This error may be reduced, however, by utilizing a sample rate that is sufficiently high as compared to the maximum rotation rate expected for the application so as to reduce error that results from angular differences between samples.

[00119] As used herein, the term "average total magnetic field value" means the average magnitude of the instantaneous vector sum of the three orthogonal magnetic field components. As used herein, the term "average magnitude of the instantaneous vector sum of the three orthogonal magnetic field components" means $B_{TwR} = \frac{\sum_{i=1}^{n}\sqrt{B_{x_i}^{2} + B_{y_i}^{2} + B_{z_i}^{2}}}{n}$ [Eqn. B1] or any substantial mathematical equivalent thereto. Here, B_{xi}, B_{yi} and B_{zi} each correspond to one of the three orthogonal magnetic field components. Typically, B_{zi} is used to denote the component magnetic field corresponding to the along-borehole axis, whereas B_{xi} and B_{yi} typically refer to cross-borehole component magnetic fields. Suitable examples of substantial mathematical equivalents to an average of the instantaneous vector magnitudes of the three orthogonal magnetic field components include, but are not limited to, $B_{TwR} = \sqrt{\frac{\sum_{i=1}^{n}\left(B_{x_i}^{2} + B_{y_i}^{2}\right)}{n} + \left(\frac{\sum_{i=1}^{n} B_{z_i}}{n}\right)^{2}}$ [Eqn. B2], $B_{TwR} = \sqrt{\frac{\sum_{i=1}^{n}\left(B_{x_i}^{2} + B_{y_i}^{2} + B_{z_i}^{2}\right)}{n}}$ [Eqn. B3], or any mathematical function that yields a substantially similar output over a desired range of interest. Eqn. B3 may be preferable in some embodiments, because this equation necessitates calculating the square root only once instead of multiple times. It is recognized that Eqn. B1 and Eqn. B3 are not exactly equal, except when $B_{xi}^2 + B_{yi}^2 + B_{zi}^2$ is equal for each i. Differences in these individual summed/square root values will result in a different error value depending on the order of the sum and square root functions. Simulations have shown Eqn. B1 to be slightly more accurate with respect to random noise on samples of B_{xi}, B_{yi} and B_{zi} than Eqn. B3. The formulation of Eqn. B2 has the advantage that random zero mean noise on samples of B_z will average to 0, making this calculation less sensitive to random noise. In certain embodiments, only two magnetometers are used to calculate the average cross-axis magnetic value. In such cases, the equation $B_{CwR} = \sqrt{\frac{\sum_{i=1}^{n}\left(B_{x_i}^{\ 2} + B_{y_i}^{\ 2}\right)}{n}}$ [Eqn. B4] may be used or any substantial mathematical equivalent thereto. As before, it is recognized that a biaxial magnetometer may be comprised of two independent sensors or may be comprised of a single sensor that integrates the functions of two independent sensors into a single sensor.

[00120] These computations may be accomplished while the drill string subassembly is rotating, such as during drilling. Accordingly, these algorithms enable the accurate computation of the average total magnetic field and average cross-axis magnetic field during drilling. In this way, by placing the magnetic field instrument device 2150 in or on a rotating portion of a drill string, an average total magnetic field and average cross-axis magnetic field may be determined for the portion of the drill string in proximity to the drill bit.

[00121] Vector magnetometers 2211, 2212 and 2213 should have a sufficiently high bandwidth such that no significant signal attenuation results at the maximum expected rotation rate.

[00122] A clock internal to microprocessor 2250 provides date and time-stamps for measured and calculated data stored in memory 2237. In certain embodiments, memory 2237 may comprise flash memory. Measured and calculated data may also be communicated to serial bus 2257 via serial bus controller 2255 for communication to a surface computer or use by other sensors and/or tools. Communication of this data to a surface computer may be accomplished by use of wireline, wired pipe, mud-pulse MWD, electro-magnetic MWD, other downhole wireless telemetry methods, such as acoustic telemetry, or any combination thereof.

Magnetic Angle Determinations

[00123] The magnetic field instrument 2150 may be further adapted to determine the angle between the axis of the borehole and the Earth's magnetic field vector, hereafter referred to as $B_{Angle}(\theta)$. In particular, microprocessor 2250 may be adapted to determine a calculated $B_{Angle}(\theta)$ of the drill string subassembly according to the formula $B_{Angle}(\theta) = \cos^{-1}\left(\frac{B_z}{B_{TwR}}\right)$ [Eqn. T1] or any substantial mathematical equivalent thereto, where B_Z refers to the along-borehole axis vector component magnetic field (B_Z). In this way, the $B_{Angle}(\theta)$ of a drill string subassembly may be used to estimate changes in borehole direction and as an indication of nearby ferromagnetic material during drilling operations.

Azimuth Determinations

[00124] The magnetic field instrument 2150 may be further adapted to determine a calculated azimuth of the drill string subassembly. Once an inclination is determined by an independent sensor, such as an inclinometer, a calculated magnetic azimuth Azm may be determined by microprocessor 2250. In particular, the formula $Azm = \cos^{-1}\left(\frac{\cos(B_{Angle}(\theta)) - \sin(Dip) * \cos(Inc)}{\cos(Dip) * \sin(Inc)}\right)$ [Eqn. A1] may be used, wherein *Inc* is an inclinometer measurement, $B_{Angle}(\theta)$ is determined according to Eqn. T1, and *Dip* is the dip angle, that is, the inclination from horizontal of the Earth's magnetic field. The dip angle can be determined from a geomagnetic model or from a stationary measurement using magnetometers and accelerometers. The sign of the Azm so determined may be either positive or negative and must be selected based on previous surveys taken while stationary. Additionally, a substantial mathematical equivalent of Eqn. A1 may alternatively be used to arrive at a substantially similar value.

Detection of External Ferromagnetic Material

[00125] The magnetic field instrument 2150 may also be further adapted to detect the presence of external ferromagnetic material during drilling. Detecting the presence of external ferromagnetic material, such as another well casing or drill string, is particularly useful for well avoidance and well intercept applications. In certain embodiments, methods for detecting the presence of external ferromagnetic material during drilling include: determining a plurality of average total magnetic fields along a section of borehole being drilled and identifying the presence of external ferromagnetic material as a portion of the section, where the average total magnetic field varies from an expected Earth's magnetic field. Again, as used herein, the term "average total magnetic field" means an average magnitude of the instantaneous vector sum of the three orthogonal magnetic field components, which may be estimated by any of the foregoing methods described herein. This adaptation also includes using only some of the components of the average total magnetic field, including at least one of B_{TwR}, B_{CwR} and B_Z.

[00126] The term "expected Earth's magnetic field" is the value for the Earth's magnetic field in absence of any external ferromagnetic material. This value may be determined by a variety of methods, including, but not limited to, measuring the Earth's magnetic field in a section of borehole known to be out of range of any external ferromagnetic material. Alternatively, this value may be inferred from a mathematical model of the geomagnetic field, a measurement on the surface, or any combination thereof.

[00127] In addition to determining the presence of external ferromagnetic material, distances to external ferromagnetic material may also be estimated. Methods for estimating distances to external ferromagnetic material include determining the amplitude and spatial frequency of the difference between the expected Earth's magnetic field and the average total magnetic field value (B_{TwR}) over a section of borehole, and comparing the amplitude and spatial frequency of a B_{TwR} difference signal to an amplitude and spatial frequency of an expected difference signal from an assumed source at an assumed distance. The expected difference signal may be estimated from theoretical data from a computer model. In general, the B_{TwR} difference signal may be determined by subtracting the Earth's total magnetic field from the B_{TwR} signal.

[00128] The amplitude and spatial frequency is characteristic of the distance to the source of the interference, which may be a well casing or another drill string. By comparing the amplitude and spatial frequency of the measured B_{TwR} difference signal to the expected difference signal from an assumed source at an assumed distance, one can estimate the distance to the external ferromagnetic material as the distance that corresponds to an assumed source and distance which produces the same amplitude and spatial frequency. Accordingly, this estimated distance may be used for well avoidance or well intercept as desired.

Instrument Integrity Verification

[00129] The average total magnetic field (B_{TwR}) that is calculated during drilling may also be used for verification of instrument integrity. An average total magnetic field (B_{TwR}) may be calculated as before during drilling. This value may then be compared to the stationary magnetic field measurements. One may compare the average total magnetic field (B_{TwR}) to the stationary total magnetic field measurement so as to determine a magnitude of error between the total magnetic field (B_{TwR}) and the stationary total magnetic field measurement. If the values diverge in the absence of external ferromagnetic material, one may infer that an instrument problem exists.

[00130] In certain embodiments, the step of measuring a stationary total magnetic field may be accomplished by measuring the stationary total magnetic field by an independent magnetic field instrumentation while the drill string subassembly is stationary. In other embodiments, the step of measuring the stationary total magnetic field may be accomplished by measuring the stationary total magnetic field with the triaxial vector magnetometer while the drill string subassembly is stationary.

[00131] It is explicitly recognized that any of the elements and features of each of the devices described herein are capable of use with any of the other devices described herein with no limitation. Furthermore, it is explicitly recognized that the steps of the methods herein may be performed in any order except unless explicitly stated otherwise or inherently required otherwise by the particular method.

[00132] In one embodiment of the present disclosure, an apparatus is disclosed. The apparatus is mechanically connected to a drill bit. The apparatus includes a bottom hole assembly having an MWD system, magnetic sensors, and a short range communications system. The short range communications system is in electrical connection with the magnetic sensors and the MWD system. The magnetic sensors are disposed within 10 feet of the drill bit.

[00133] The magnetic sensors can be located within a non-magnetic carrier sub assembly.

[00134] The apparatus can include a wireline connection, a mud pulse telemetry system or an electromagnetic wireless transmission system in electrical connection with the MWD system and adapted to communicate with a surface receiver.

[00135] Embodiments of the short range communications system can include an insulated electrode, an insulated gap electrode, a cross-coil antenna, or a toroid antenna.

[00136] The apparatus can include a mud motor or rotary steerable system. The mud motor can be formed of non-magnetic materials.

[00137] The mud motor can have a housing, which can include one or more housing unit sections. The housing can define an axis length of a main housing axis. The mud motor can include a motor stator for a motor driven by drilling fluid and a motor rotor for the motor adapted to be driven by drilling fluid.

[00138] The mud motor can also include a bent subassembly at a lower end of the mud motor. The bent subassembly can provide a relatively small angular deviation between the main housing axis and a bent subassembly axis that is defined by the bent subassembly. An output shaft can extend within the bent subassembly and be adapted to drive the drill bit. A bearing assembly can be adapted to support the output shaft for rotation within the housing. A torsion bar or flexible shaft connects the motor rotor to the output shaft. The torsion bar or flexible shaft accommodates both eccentric motion of the motor rotor and bend and relative motion between the main housing axis and the bent subassembly axis.

[00139] A sensor and data transmission assembly can be located on the main housing. The sensor and data transmission assembly can be disposed in a parallel relationship with the torsion bar or flexible shaft, and can extend generally at the same longitudinal distance along the main housing as the torsion bar or flexible shaft extends. In an embodiment, the magnetic sensors are located within the sensor and data transmission assembly.

[00140] In one or more embodiments, the housing unit sections extend lengthwise, generally longitudinally. The torsion bar or flexible shaft also extends generally longitudinally. The sensor and data transmission assembly can be offset laterally from the torsion bar or flexible shaft, which extends within the housing unit sections.

[00141] The sensor and data transmission assembly can include an insulated electrically conductive element that extends longitudinally in a position that is recessed inwardly relative to a cylinder defined by an outer surface of the housing unit sections. The insulated electrically conductive element can also be spaced laterally from the torsion bar or flexible shaft, and drilling fluid can flow between the insulated electrically conductive element and the torsion bar or flexible shaft.

[00142] In an embodiment, the housing can define a side recess at one side of the output shaft. The side recess can contain the sensor and data transmission assembly, and a fluid flow path can be present between the output shaft and the side recess.

[00143] An embodiment of the apparatus can include magnetic compensation firmware. The magnetic compensation firmware can be in electrical connection with the magnetic sensors.

[00144] In another embodiment, the apparatus can include a mud motor having a housing that defines a longitudinal housing axis. The housing can have an upper end and a lower end.

[00145] The mud motor can include a motor with a rotor that is adapted to be driven by drilling fluids. A first drive coupling can be coupled between the rotor and a first driven rod, a second drive coupling can be coupled between the first driven rod and a connecting shaft, a third drive coupling can be coupled between the connecting shaft and a second driven rod, and a fourth drive coupling can be coupled between the second driven rod and a motor bearing section. The connecting shaft can extend through an offset bore in the housing and transmit power through the offset bore to the drill bit. In an embodiment, first and second bearings can be adapted to prevent the connecting shaft from rubbing against an internal surface of the housing.

[00146] The mud motor can have a recess disposed on the housing. The sensor and data transmission assembly can be disposed within the recess. The sensor and data transmission assembly can include the magnetic sensors, and magnetic compensation firmware can be in electrical connection with the magnetic sensors.

[00147] In another embodiment, the magnetic sensors can be located within a first carrier sub assembly. The short range communications system can include a lower electrode mechanically connected to the first carrier sub assembly. The lower electrode can be insulated from the first carrier sub assembly and externally exposed to an environment of the first carrier sub assembly. The short range communications system can include a first transmitter electrically connected to the lower electrode and adapted to modulate power to the lower electrode so as to minimize power consumption and maintain a sufficient signal-to-noise ratio in response to a drilling environment.

[00148] The short range communications system can include a communication management controller in communication with the first transmitter for driving a data modulated current into the lower electrode by way of the first transmitter.

[00149] The short range communications system can include a second downhole sub and an upper electrode mechanically connected to the second downhole sub. The upper electrode can be insulated from the second downhole sub and externally exposed to an environment of the

second downhole sub. A receiver can be electrically connected to the upper electrode and adapted to receive a signal from the upper electrode. The signal can represent measurement data.

[00150] The short range communications system can include a surface uplink transmitter in communication with the receiver and adapted to communicate the measurement data from the receiver to the surface. The surface uplink transmitter can make use of wireline, wired pipe, mud-pulse MWD, electro-magnetic MWD, other downhole wireless telemetry methods, such as acoustic telemetry, or any combination thereof.

[00151] In an embodiment, the lower electrode can be recessed with respect to an outer surface of the first carrier sub assembly. The lower electrode can be adapted to transmit electrical current through a drilling mud or formation, and the upper electrode can be adapted to receive electrical current through the drilling mud or formation. The lower electrode can be situated below the motor, and the upper electrode can be situated above the motor.

[00152] Embodiments of the apparatus can include a rotary steerable device in communication with the receiver for adjusting a course of drilling based on the measurement data. A data storage device can also be in communication with the receiver for storing the measurement data.

[00153] In another embodiment, the short range communications system is an acoustic system.

[00154] In another embodiment of the present disclosure, a method is disclosed. The method can include supplying a bottom hole assembly that includes an MWD system, magnetic sensors, a mud motor or rotary steerable system, and a short range communications system.

[00155] The MWD system can have navigation sensors and acceleration sensors.

[00156] The bottom hole assembly can be mechanically connected to a drill bit, and the magnetic sensors can be disposed within 10 feet of the drill bit.

[00157] The method can further include measuring a magnetic field with the magnetic sensors, and communicating the measurement of the magnetic field from the magnetic sensors to the MWD system through the short range communications system. After communicating the measurement of the magnetic field, the method can further include compensating the measurement of the magnetic field. Compensating the measurement of the magnetic field can include:

[00158] (a) supplying correlated clocks to the MWD system and the magnetic sensors,

[00159] (b) sampling the navigation sensors and the magnetic sensors at predetermined intervals to form MWD navigation data and magnetic sensor data that has a magnetic coordinate system,

[00160] (c) establishing a reference coordinate system for the navigation sensors and the magnetic sensors,

[00161] (d) rotating the magnetic coordinate system to match the reference coordinate system using the acceleration sensors,

[00162] (e) comparing the magnetic sensor data and the MWD navigation data,

[00163] (f) compensating the magnetic sensor data based on the MWD navigation data, and

[00164] (g) rotating the magnetic sensor data back to corrected values.

[00165] The method can further include determining a location of a magnetic source. Determining the location of the magnetic source can include determining vector components of a total magnetic field vector at each of a plurality of measured depth locations along a sub-surface arbitrary path in a sub-surface magnetic field. The vector components at each measured depth location can include a first vector component in a direction of the sub-surface arbitrary path, and a second vector component lying in a plane normal to the sub-surface arbitrary path.

[00166] Determining the location of the magnetic source can further include determining a direction of a gravity vector at each of the plurality of measured depth locations along the sub-surface arbitrary path.

[00167] Determining the location of the magnetic source can further include using the determined direction of the gravity vector at each measured depth location to resolve the determined total magnetic field vector components into resolved horizontal and vertical components of the total magnetic field vector. The resolved horizontal and vertical components can include a horizontal component in the direction of the sub-surface arbitrary path, and a horizontal component perpendicular to the sub-surface arbitrary path and lying in a vertical plane that contains the first vector in the direction of the sub-surface arbitrary path.

[00168] Determining the location of the magnetic source can further include estimating the direction of the sub-surface arbitrary path with respect to a fixed magnetic field component path at each measured depth location as a mathematical function of distance of the measured depth location along the sub-surface arbitrary path.

[00169] Determining the location of the magnetic source can further include estimating a magnitude of a fixed horizontal magnetic field of the fixed magnetic field component.

[00170] Determining the location of the magnetic source can further include calculating estimated horizontal magnetic field components from the estimated fixed horizontal magnetic field and the mathematical function at each measured depth location.

[00171] Determining the location of the magnetic source can further include adjusting parameters of the mathematical function and the estimate of the fixed horizontal magnetic field to match one of the following variations in the estimated horizontal magnetic field components with the measured horizontal magnetic field components: fixed variations, and fixed and lower order variations.

[00172] Determining the location of the magnetic source can further include subtracting the determined Earth magnetic field from measured total magnetic field vector along a wellbore.

[00173] Determining the location of the magnetic source can further include deriving an estimated magnetic field of the magnetic source from a parametric model of the magnetic source descriptive of a position and attitude of the magnetic source of magnetic field disturbance.

[00174] Determining the location of the magnetic source can further include comparing the determined magnetic field of the magnetic source with the estimated magnetic field.

[00175] Determining the location of the magnetic source can further include adjusting parameters of the parametric model to minimize the difference between the determined magnetic field and the parametric model estimate of the magnetic field of the magnetic source along the wellbore.

[00176] In an embodiment of the method, the short range communications system can include an insulated electrode, an insulated gap electrode, a cross-coil antenna, or a toroid antenna.

[00177] The method can further include supplying a wireline connection, a mud pulse telemetry system or an electromagnetic wireless transmission system in electrical connection with the MWD system, and communicating magnetic sensor data to the surface. The wireline connection, mud pulse telemetry system or electromagnetic wireless transmission system can be adapted to communicate with a surface receiver.

[00178] In an embodiment of the method, the magnetic sensors can include a triaxial vector magnetometer affixed to a drill string subassembly and adapted to measure three orthogonal magnetic field components. The triaxial vector magnetometer can include three vector magnetometers.

[00179] The method can further include allowing the drill string subassembly to rotate, and determining an average total magnetic field value (B_{TwR}) as an average magnitude of an instantaneous vector sum of the three orthogonal magnetic field components while the drill string subassembly is rotating. The average total magnetic field value (B_{TwR}) can be computed according to the following formula or a substantial mathematical equivalent thereto:

$$B_{TwR} = \frac{\sum_{i=1}^{n} \sqrt{B_{xi}^{2} + B_{y_i}^{2} + B_{zi}^{2}}}{n}$$

, where B_{xi}, B_{yi}, and B_{zi} each correspond to one of the three orthogonal magnetic field components.

[00180] The total magnetic field value (B_{TwR}) can be computed according to at least one of the following formulas:

[00181] $$B_{TwR} = \frac{\sum_{i=1}^{n} \sqrt{B_{xi}^{2} + B_{y_i}^{2} + B_{zi}^{2}}}{n};$$

[00182] $$B_{TwR} = \sqrt{\frac{\sum_{i=1}^{n} \left(B_{xi}^{2} + B_{y_i}^{2}\right)}{n} + \left(\frac{\sum_{i=1}^{n} B_{zi}}{n}\right)^{2}}$$; and

[00183] $$\sqrt{\frac{\sum_{i=1}^{n} \left(B_{xi}^{2} + B_{y_i}^{2} + B_{zi}^{2}\right)}{n}}$$

, where B_{xi}, B_{yi}, and B_{zi} each correspond to one of the three orthogonal magnetic field components. For example, Bzi can correspond to an along-borehole axis, and Bxi and Byi can correspond to cross-borehole axes.

[00184] The method can further include determining an along-borehole axis vector component magnetic field value (B_z), and determining a calculated $B_{Angle}(\theta)$ of the drill string subassembly. The calculated $B_{Angle}(\theta)$ of the drill string subassembly can be determined according to the formula:

[00185] $B_{Angle}(\theta) = \cos^{-1}\left(\frac{B_z}{B_{TwR}}\right)$ or a substantial mathematical equivalent thereto.

[00186] In another embodiment, the method can include determining an along-borehole axis vector component magnetic field (B_z), and determining a calculated $B_{Angle}(\theta)$ of the drill string subassembly according to the following formula:

[00187] $B_{Angle}(\theta) = \cos^{-1}\left(\frac{B_z}{B_{TwR}}\right)$.

[00188] The method can further include temporarily ceasing rotation of the drill string subassembly, measuring an inclination and an azimuth of the drill string subassembly while the drill string subassembly is stationary so as to determine an initial stationary azimuth and inclination, allowing the drill string subassembly to rotate during drilling, and determining a calculated azimuth (Azm) during drilling. The calculated azimuth (Azm) can be determined according to the following formula:

[00189] $Azm = \cos^{-1}\left(\frac{\cos(B_{Angle}(\theta)) - \sin(Dip) * \cos(Inc)}{\cos(Dip) * \sin(Inc)}\right)$, where *Inc* is inclination during drilling, *Dip* is an inclination from horizontal of the Earth's magnetic field, and $B_{Angle}(\theta)$ is the calculated $B_{Angle}(\theta)$.

[00190] Embodiments of the method can include avoiding a well collision using the calculated Azm to determine a borehole direction. Also, the method can include intercepting a well using the calculated Azm to determine a borehole direction. The method can include using the calculated $B_{Angle}(\theta)$ and the calculated Azm for well collision avoidance, well intercept, or both.

[00191] The method can further include outputting a value. The value can be the B_{TwR}, calculated $B_{Angle}(\theta)$, calculated inclination, or calculated Azm. Outputting the value can include storing the value in a memory, transmitting the value to a surface computer, or both.

[00192] An embodiment of the method can further include providing an inclinometer affixed to the drill string subassembly, measuring an inclination using the inclinometer, temporarily ceasing rotation of the drill string subassembly, measuring an azimuth of the drill string subassembly while the drill string subassembly is stationary so as to determine an initial stationary azimuth, allowing the drill string subassembly to rotate during drilling, and determining a calculated azimuth during drilling. The calculated azimuth can be determined according to the following formula:

[00193] $Azm = \cos^{-1}\left(\frac{\cos(B_{Angle}(\theta)) - \sin(Dip) * \cos(Inc)}{\cos(Dip) * \sin(Inc)}\right)$, where Inc is inclination during drilling and Dip is an inclination from horizontal of the Earth's magnetic field.

[00194] The foregoing outlines features of several embodiments so that a person of ordinary skill in the art may better understand the aspects of the present disclosure. Such features may be replaced by any one of numerous equivalent alternatives, only some of which are disclosed herein. One of ordinary skill in the art should appreciate that they may readily use the present disclosure as a basis for designing or modifying other processes and structures for carrying out the same purposes and/or achieving the same advantages of the embodiments introduced herein. One of ordinary skill in the art should also realize that such equivalent constructions do not depart from the spirit and scope of the present disclosure, and that they may make various changes, substitutions and alterations herein without departing from the spirit and scope of the present disclosure.

[00195] The Abstract at the end of this disclosure is provided to comply with 37 C.F.R. §1.72(b) to allow the reader to quickly ascertain the nature of the technical disclosure. It is submitted with the understanding that it will not be used to interpret or limit the scope or meaning of the claims.

[00196] Moreover, it is the express intention of the applicant not to invoke 35 U.S.C. §112, paragraph 6 for any limitations of any of the claims herein, except for those in which the claim expressly uses the word "means" together with an associated function.

What is claimed is:

1. An apparatus mechanically connected to a drill bit comprising:

a bottom hole assembly comprising an MWD system, magnetic sensors, and a short range communications system, wherein the short range communications system is in electrical connection with the magnetic sensors and the MWD system, and wherein the magnetic sensors are within 10 feet of the drill bit.

2. The apparatus of claim 1, wherein the magnetic sensors are located within a non-magnetic carrier sub assembly.

3. The apparatus of claim 1, further comprising a wireline connection, a mud pulse telemetry system or an electromagnetic wireless transmission system in electrical connection with the MWD system and adapted to communicate with a surface receiver.

4. The apparatus of claim 1, wherein the short range communications system comprises an insulated electrode, an insulated gap electrode, a cross-coil antenna, or a toroid antenna.

5. The apparatus of claim 1, further comprising a mud motor or rotary steerable system.

6. The apparatus of claim 1, further comprising a mud motor, wherein the mud motor comprises non-magnetic materials.

7. The apparatus of claim 6, wherein the mud motor further comprises:

a housing including one or more housing unit sections and defining an axis length of a main housing axis;

a motor stator for a motor driven by drilling fluid;

a motor rotor for the motor adapted to be driven by the drilling fluid;

a bent subassembly at a lower end of the mud motor, the bent subassembly providing a relatively small angular deviation between said main housing axis and a bent subassembly axis defined by the bent subassembly;

an output shaft extending within the bent subassembly adapted to drive the drill bit;

a bearing assembly adapted to support the output shaft for rotation within the housing;

a torsion bar or flexible shaft connecting the motor rotor to the output shaft, the torsion bar or flexible shaft accommodating both eccentric motion of the motor rotor and bend and relative motion between the main housing axis and the bent subassembly axis; and

a sensor and data transmission assembly located on the main housing in a parallel relationship with the torsion bar or flexible shaft, and extending generally at the same longitudinal distance along the main housing as the torsion bar or flexible shaft, wherein the magnetic sensors are located within the sensor and data transmission assembly.

8. The apparatus of claim 7, wherein the one or more housing unit sections extend lengthwise generally longitudinally, wherein the torsion bar or flexible shaft extends generally longitudinally, and wherein the sensor and data transmission assembly is offset laterally from the torsion bar or flexible shaft which extends within the one or more housing unit sections.

9. The apparatus of claim 8, wherein the sensor and data transmission assembly includes an insulated electrically conductive element which extends longitudinally, and is also spaced laterally from said torsion bar or flexible shaft, whereby the drilling fluid is flowable therebetween.

10. The apparatus of claim 9, wherein the housing defines a side recess at one side of the output shaft, wherein the side recess contains said sensor and data transmission assembly, and wherein a fluid flow path is between the output shaft and the side recess.

11. The apparatus of claim 7, further comprising magnetic compensation firmware, wherein the magnetic compensation firmware is in electrical connection with the magnetic sensors.

12. The apparatus of claim 1, further comprising a mud motor, wherein the mud motor comprises:

a housing defining a longitudinal housing axis, wherein the housing has an upper end and a lower end;

a motor including a rotor, wherein the rotor is adapted to be driven by drilling fluids;

a first drive coupling coupled between the rotor and a first driven rod;

a second drive coupling coupled between the first driven rod and a connecting shaft;

a third drive coupling coupled between the connecting shaft and a second driven rod; and

a fourth drive coupling coupled between the second driven rod and a motor bearing section;

wherein the connecting shaft extends through an offset bore in the housing and transmits power through the offset bore to the drill bit.

13. The apparatus of claim 12, further comprising first and second bearings adapted to prevent the connecting shaft from rubbing against an internal surface of the housing.

14. The apparatus of claim 12, further comprising a recess disposed on the housing.

15. The apparatus of claim 14, wherein a sensor and data transmission assembly is disposed within the recess.

16. The apparatus of claim 15, wherein the sensor and data transmission assembly includes the magnetic sensors.

17. The apparatus of claim 12, further comprising magnetic compensation firmware, wherein the magnetic compensation firmware is in electrical connection with the magnetic sensors.

18. The apparatus of claim 1, wherein the magnetic sensors are located within a first carrier sub assembly.

19. The apparatus of claim 18, wherein the short range communications system further comprises:

a lower electrode mechanically connected to the first carrier sub assembly, wherein the lower electrode is insulated from the first carrier sub assembly, and wherein the lower electrode is externally exposed to an environment of the first carrier sub assembly;

a first transmitter electrically connected to the lower electrode, wherein the first transmitter is adapted to modulate power to the lower electrode so as to minimize power consumption and maintain a sufficient signal to noise ratio in response to a drilling environment;

a communication management controller in communication with the first transmitter for driving a data modulated current into the lower electrode by way of the first transmitter;

a second downhole sub;

an upper electrode mechanically connected to the second downhole sub, wherein the upper electrode is insulated from the second downhole sub, and wherein the upper electrode is externally exposed to an environment of the second downhole sub;

a receiver electrically connected to the upper electrode, wherein the receiver is adapted to receive a signal from the upper electrode, and wherein the signal represents measurement data; and

a surface uplink transmitter in communication with the receiver, wherein the surface uplink transmitter is adapted to communicate the measurement data from the receiver to the surface.

20. The apparatus of claim 19, wherein the lower electrode is recessed with respect to an outer surface of the first carrier sub assembly.

21. The apparatus of claim 19, wherein the lower electrode is adapted to transmit electrical current through a drilling mud or formation, and wherein the upper electrode is adapted to receive electrical current through the drilling mud or formation.

22. The apparatus of claim 19, wherein the lower electrode is situated below a motor, and wherein the upper electrode is situated above the motor.

23. The apparatus of claim 19, further comprising a rotary steerable device in communication with the receiver for adjusting a course of drilling based on the measurement data.

24. The apparatus of claim 19, further comprising a data storage device in communication with the receiver for storing the measurement data.

25. The apparatus of claim 19, wherein the surface uplink transmitter is a mud pulse type transmitter.

26. The apparatus of claim 19, wherein the surface uplink transmitter is an electric field surface conduction transmitter.

27. The apparatus of claim 19, wherein the surface uplink transmitter is an acoustic transmitter.

28. The apparatus of claim 19, wherein the surface uplink transmitter uses a wired collar uplink.

29. The apparatus of claim 1, wherein the short range communications system is an acoustic system.

30. A method comprising:

supplying a bottom hole assembly comprising:

an MWD system, wherein the MWD system has navigation sensors and acceleration sensors;

magnetic sensors;

a mud motor or rotary steerable system; and

a short range communications system, wherein the bottom hole assembly is mechanically connected to a drill bit, and wherein the magnetic sensors are within 10 feet of the drill bit;

measuring a magnetic field with the magnetic sensors; and

communicating the measurement of the magnetic field from the magnetic sensors to the MWD system through the short range communications system.

31. The method of claim 30, further comprising, after the step of communicating the measurement of the magnetic field, compensating the measurement of the magnetic field.

32. The method of claim 31, wherein the step of compensating the measurement of the magnetic field comprises:

supplying correlated clocks to the MWD system and the magnetic sensors;

sampling the navigation sensors and the magnetic sensors at predetermined intervals to form MWD navigation data and magnetic sensor data, wherein the magnetic sensor data has a magnetic coordinate system;

establishing a reference coordinate system for the navigation sensors and the magnetic sensors;

rotating the magnetic coordinate system to match the reference coordinate system using the acceleration sensors;

comparing the magnetic sensor data and the MWD navigation data;

compensating the magnetic sensor data based on the MWD navigation data; and

rotating the magnetic sensor data back to corrected values.

33. The method of claim 30, further comprising: determining a location of a magnetic source.

35. The method of claim 33, wherein the step of determining the location of the magnetic source comprises:

determining vector components of a total magnetic field vector at each of a plurality of measured depth locations along a sub-surface arbitrary path in a sub-surface magnetic field, said vector components at each measured depth location comprising a first vector component in a direction of said sub-surface arbitrary path, and a second vector component lying in a plane normal to said sub-surface arbitrary path;

determining a direction of a gravity vector at each of said plurality of measured depth locations along said sub-surface arbitrary path;

using said determined direction of the gravity vector at each measured depth location to resolve said determined total magnetic field vector components into resolved horizontal and vertical components of said total magnetic field vector, said resolved horizontal and vertical components comprising a horizontal component in the direction of said sub-surface arbitrary path, and a horizontal component perpendicular to said sub-surface arbitrary path and lying in a vertical plane which contains said first vector in the direction of said sub-surface arbitrary path;

estimating the direction of said sub-surface arbitrary path with respect to a fixed magnetic field component path of a fixed magnetic field component at each said measured depth location as a mathematical function of distance of said measured depth location along the sub-surface arbitrary path;

estimating a magnitude of a fixed horizontal magnetic field of said fixed magnetic field component;

calculating estimated horizontal magnetic field components from said estimated fixed horizontal magnetic field and said mathematical function at each said measured depth location;

adjusting parameters of said mathematical function and said estimate of the fixed horizontal magnetic field to match one of the following variations in said estimated horizontal magnetic field components with said measured horizontal magnetic field components:

fixed variations; and

fixed and lower order variations;

subtracting said determined Earth magnetic field from measured total magnetic field vector along a wellbore;

deriving an estimated magnetic field of the magnetic source from a parametric model of said magnetic source descriptive of a position and attitude of said magnetic source of magnetic field disturbance;

comparing said determined magnetic field of said magnetic source with said estimated magnetic field;

adjusting parameters of said parametric model to minimize the difference between said determined magnetic field and said parametric model estimate of the magnetic field of the magnetic source along the wellbore.

35. The method of claim 30, wherein the short range communications system comprises an insulated electrode, an insulated gap electrode, a cross-coil antenna, or a toroid antenna.

36. The method of claim 30, further comprising:

supplying a wireline connection, a mud pulse telemetry system or an electromagnetic wireless transmission system in electrical connection with the MWD system and adapted to communicate with a surface receiver; and

communicating magnetic sensor data to the surface.

37. The method of claim 30, wherein the magnetic sensors comprise a triaxial vector magnetometer affixed to a drill string subassembly, wherein the triaxial vector magnetometer is adapted to measure three orthogonal magnetic field components.

38. The method of claim 37, further comprising:

allowing the drill string subassembly to rotate; and

determining an average total magnetic field value (B_{TwR}) as an average magnitude of an instantaneous vector sum of the three orthogonal magnetic field components during the step of allowing the drill string subassembly to rotate.

39. The method of claim 38, wherein the triaxial vector magnetometer comprises three vector magnetometers.

40. The method of claim 38, wherein the average total magnetic field value (B_{TwR}) is computed according to the following formula or a substantial mathematical equivalent thereto:

$$B_{TwR} = \frac{\sum_{i=1}^{n} \sqrt{B_{xi}^{2} + B_{y_i}^{2} + B_{zi}^{2}}}{n}$$, wherein B_{xi}, B_{yi}, and B_{zi} each correspond to one of the three orthogonal magnetic field components.

41. The method of claim 38, wherein the total magnetic field value (B_{TwR}) is computed according to a formula selected from the group consisting of:

$$B_{TwR} = \frac{\sum_{i=1}^{n} \sqrt{B_{xi}^{2} + B_{y_i}^{2} + B_{zi}^{2}}}{n};$$

$$B_{TwR} = \sqrt{\frac{\sum_{i=1}^{n}\left(B_{x_i}^{\ 2} + B_{y_i}^{\ 2}\right)}{n} + \left(\frac{\sum_{i=1}^{n} B_{z_i}}{n}\right)^2}$$; and

$\sqrt{\frac{\sum_{i=1}^{n}\left(B_{x_i}^{\ 2} + B_{y_i}^{\ 2} + B_{z_i}^{\ 2}\right)}{n}}$, wherein B_{xi}, B_{yi}, and B_{zi} each correspond to one of the three orthogonal magnetic field components.

42. The method of claim 41, wherein B_{zi} corresponds to an along-borehole axis, and wherein B_{xi} and B_{yi} correspond to cross-borehole axes.

43. The method of claim 41, further comprising:

determining an along-borehole axis vector component magnetic field value (B_z); and

determining a calculated $B_{Angle}(\theta)$ of the drill string subassembly according to the formula $B_{Angle}(\theta) = \cos^{-1}\left(\frac{B_z}{B_{TwR}}\right)$ or a substantial mathematical equivalent thereto.

44. The method of claim 41, further comprising:

determining an along-borehole axis vector component magnetic field (B_z); and

determining a calculated $B_{Angle}(\theta)$ of the drill string subassembly according to the formula $B_{Angle}(\theta) = \cos^{-1}\left(\frac{B_z}{B_{TwR}}\right)$.

45. The method of claim 44, further comprising:

temporarily ceasing rotation of the drill string subassembly;

measuring an inclination and an azimuth of the drill string subassembly while the drill string subassembly is stationary so as to determine an initial stationary azimuth and inclination;

allowing the drill string subassembly to rotate during drilling; and determining a calculated azimuth (Azm) during drilling according to the formula:

$$Azm = \cos^{-1}\left(\frac{\cos(B_{Angle}(\theta)) - \sin(Dip) * \cos(Inc)}{\cos(Dip) * \sin(Inc)}\right)$$

, wherein *Inc* is inclination during drilling, wherein *Dip* is an inclination from horizontal of the Earth's magnetic field, and wherein B_{Angle} is the calculated $B_{Angle}(\theta)$.

46. The method of claim 45, further comprising avoiding a well collision using the calculated Azm to determine a borehole direction.

47. The method of claim 45, further comprising intercepting a well using the calculated Azm to determine a borehole direction.

47. The method of claim 45, further comprising using the calculated $B_{Angle}(\theta)$ and the calculated Azm for one of: well collision avoidance and well intercept.

49. The method of claim 45, further comprising the step of outputting a value, wherein the value is selected from the group consisting of: the B_{TwR}, the calculated $B_{Angle}(\theta)$, the calculated inclination, and the calculated Azm, wherein the step of outputting is selected from the group consisting of: storing the value in a memory and transmitting the value to a surface computer.

50. The method of claim 41, further comprising:

providing an inclinometer affixed to the drill string subassembly;

measuring an inclination using the inclinometer;

temporarily ceasing rotation of the drill string subassembly;

measuring an azimuth of the drill string subassembly while the drill string subassembly is stationary so as to determine an initial stationary azimuth;

allowing the drill string subassembly to rotate during drilling; and

determining a calculated azimuth during drilling according to the formula

$$Azm = \cos^{-1}\left(\frac{\cos(B_{Angle}(\theta)) - \sin(Dip) * \cos(Inc)}{\cos(Dip) * \sin(Inc)}\right)$$

, wherein *Inc* is inclination during drilling and *Dip* is an inclination from horizontal of the Earth's magnetic field.

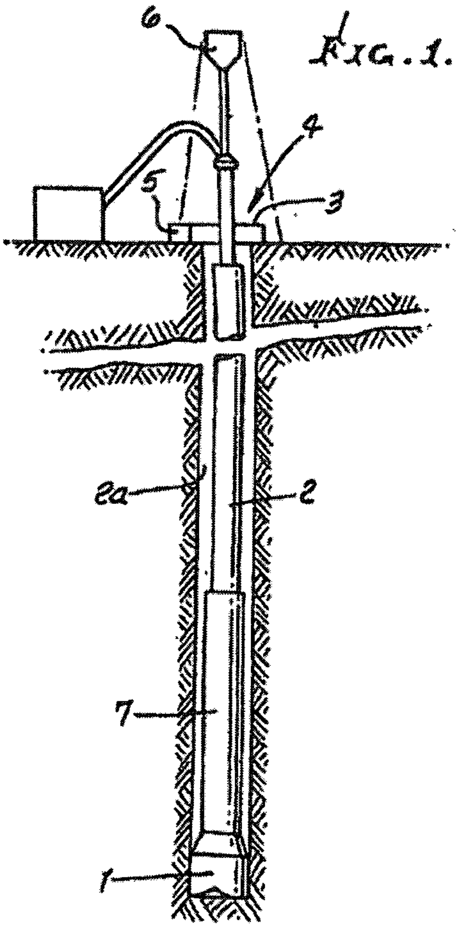
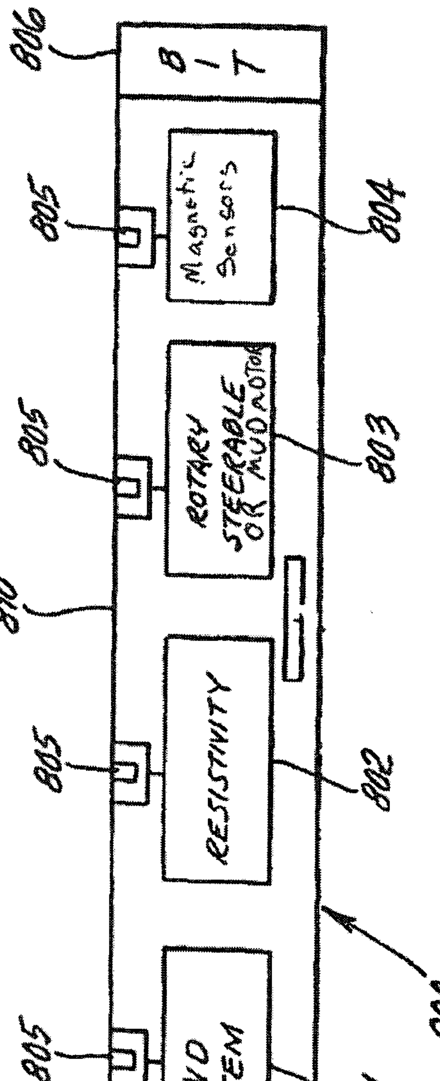


FIG. 1.

FIG. 2


806
BIT
805
Magnetic Sensors
804
805
ROTARY STEERABLE OR MUD MOTOR
803
810
805
RESISTIVITY
802
805
MWD SYSTEM
801
800

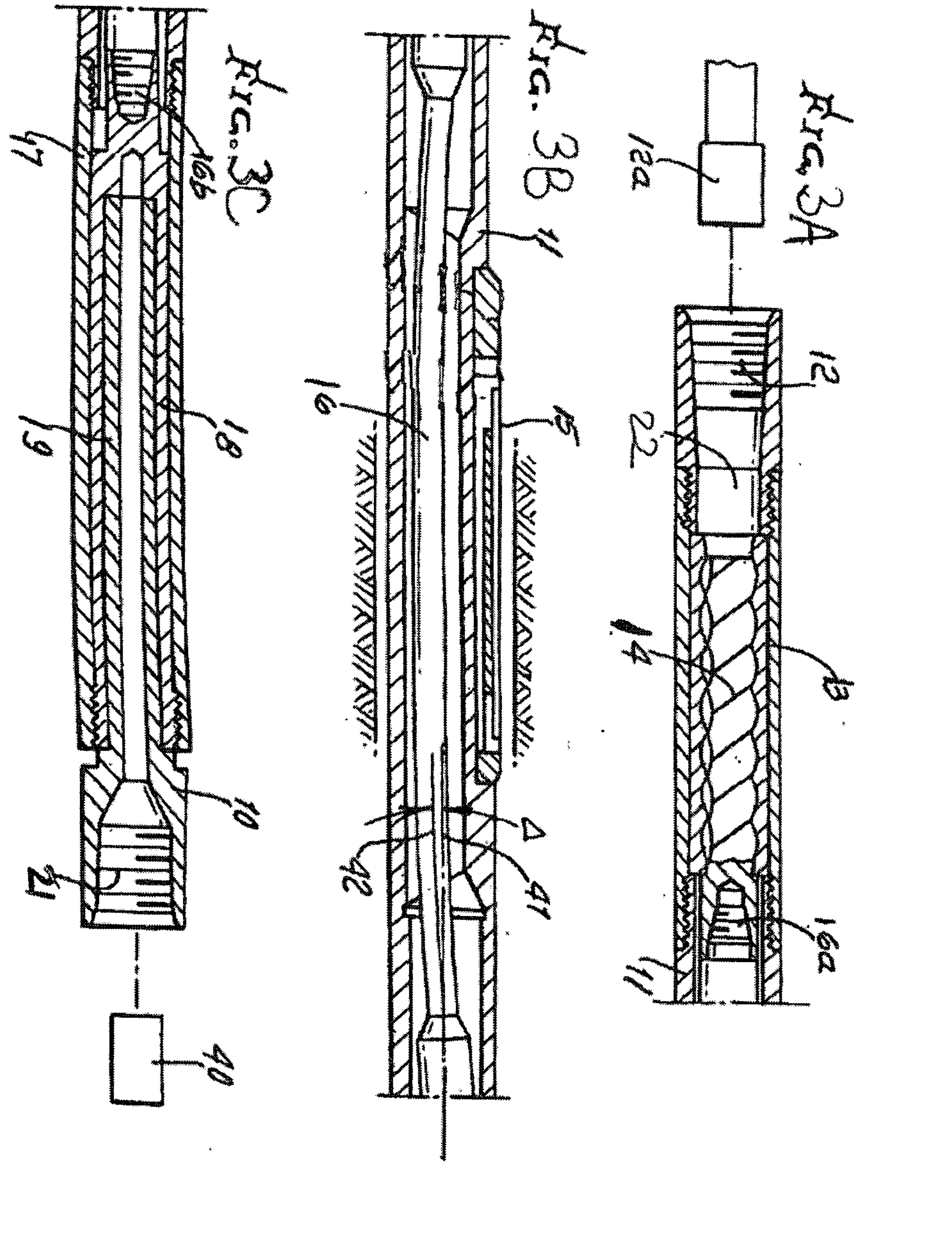


FIG. 3A
FIG. 3B
FIG. 3C
12a
12
22
14
13
16a
11
16
15
4
41
42
47
16b
19
18
10
21
40

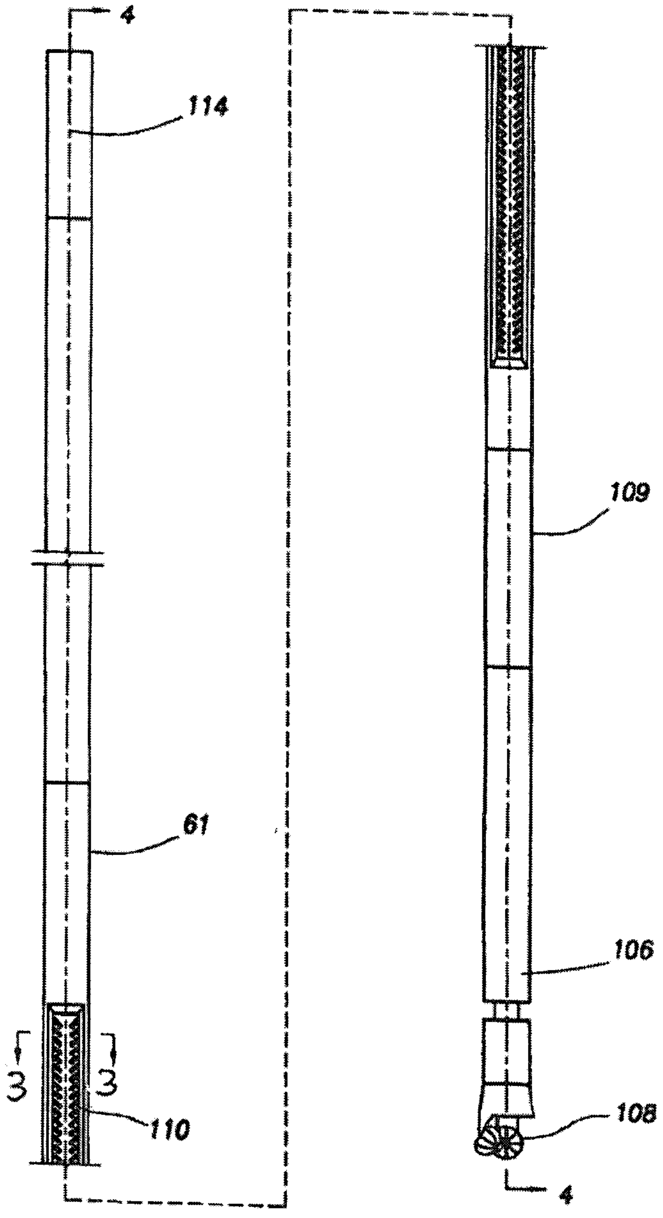


FIG. 4A

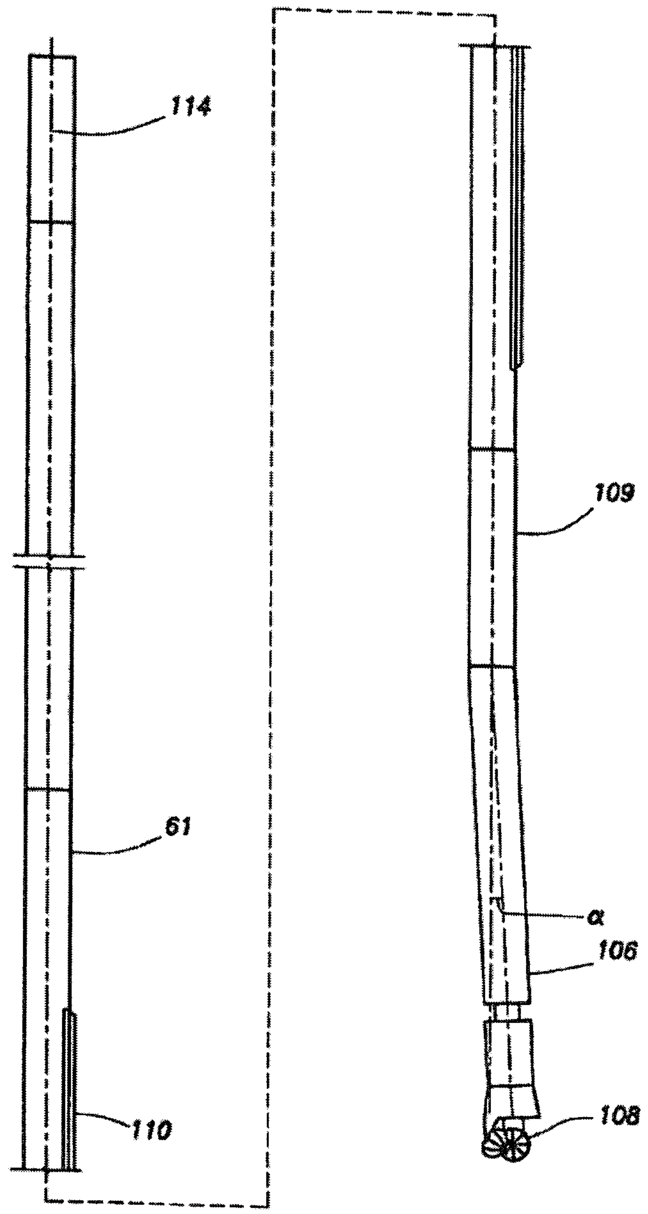


FIG. 4B

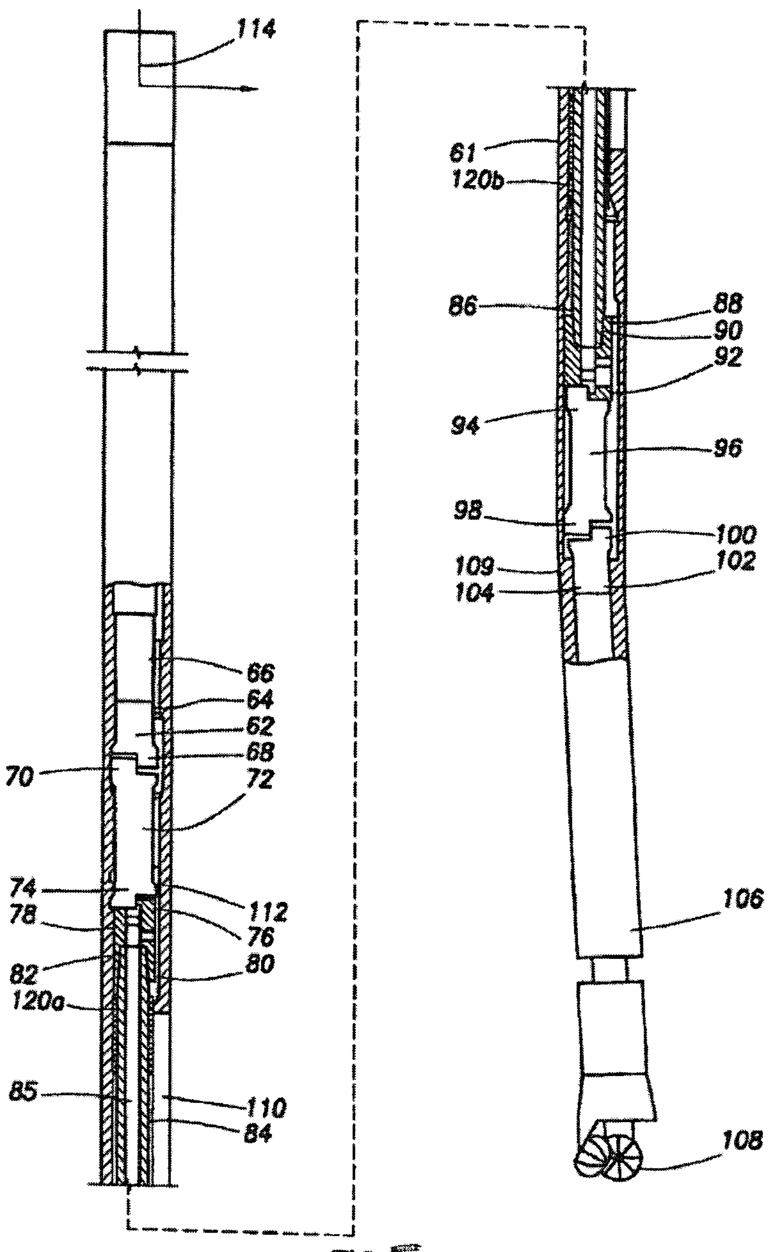
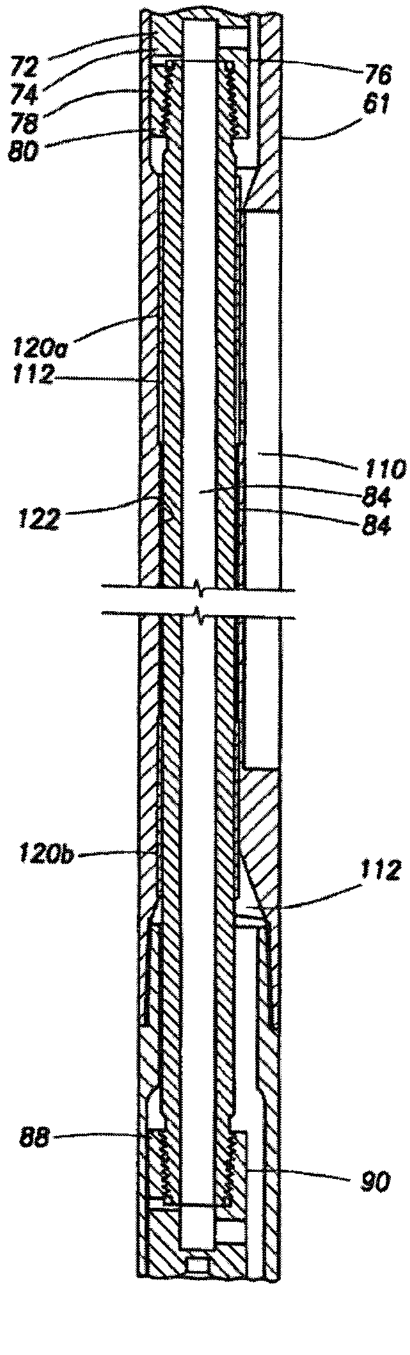

114
61
120b
86
88
90
92
94
96
98
100
109
102
104
66
64
62
68
70
72
74
112
78
76
82
80
120a
85
110
84
106
108

FIG. 5

FIG. 5A



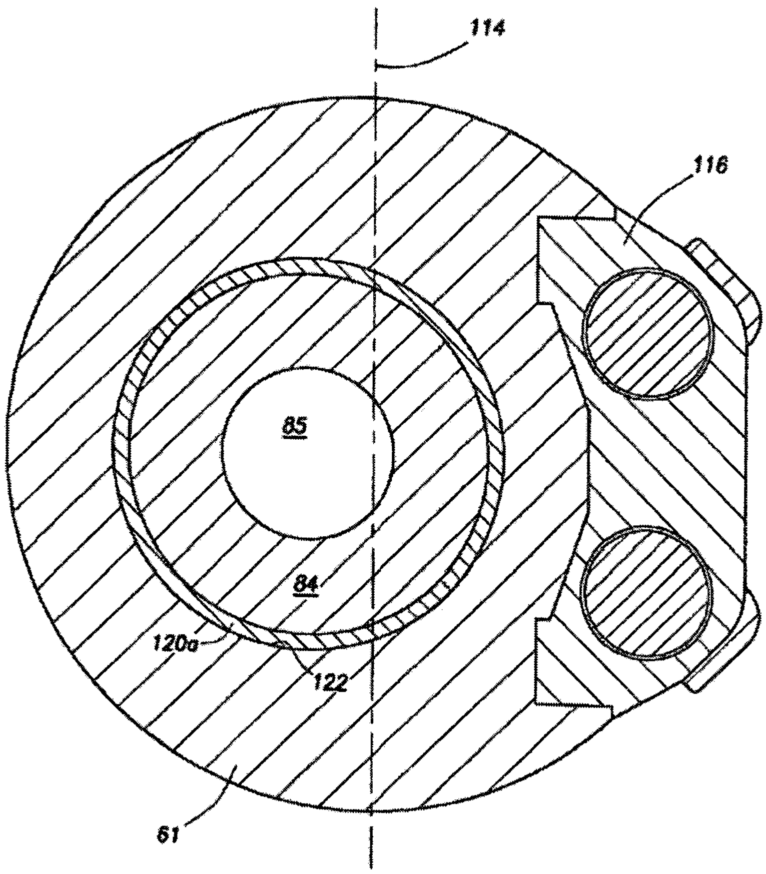


FIG. 6

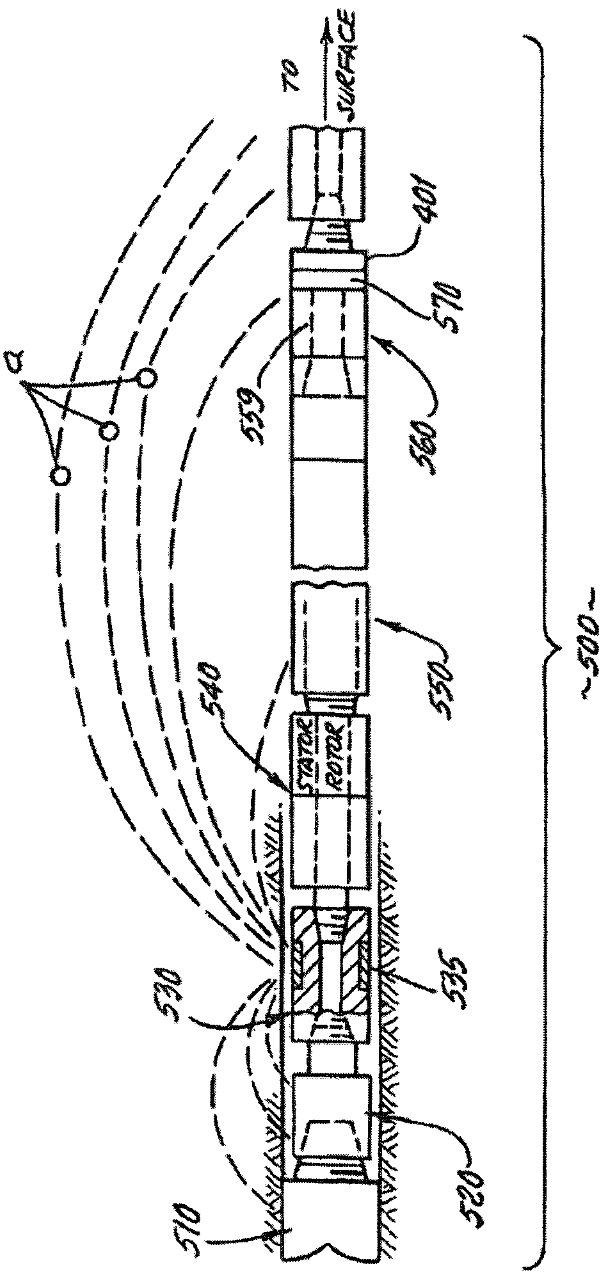

70
SURFACE
401
570
559
560
a
550
540
STATOR
ROTOR
530
535
520
510
500

FIG. 7

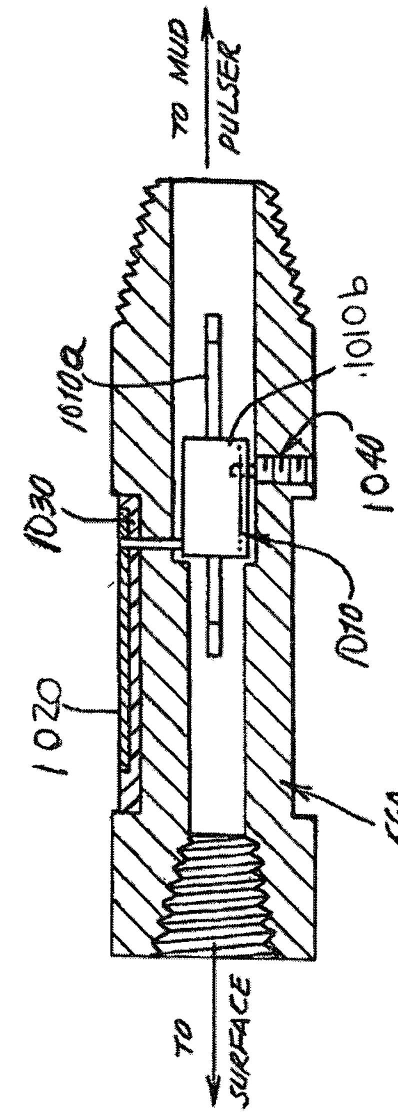

TO MUD PULSER
1010a
1010b
1030
1040
1020
1010
560
TO SURFACE

FIG. 7A

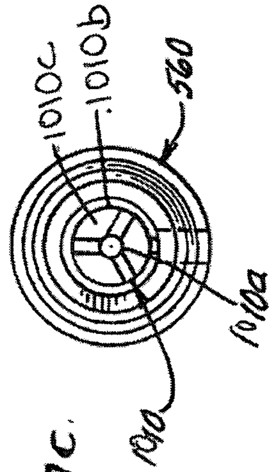

1010c
1010b
560
1010a
1010

FIG. 7C

FIG. 7B

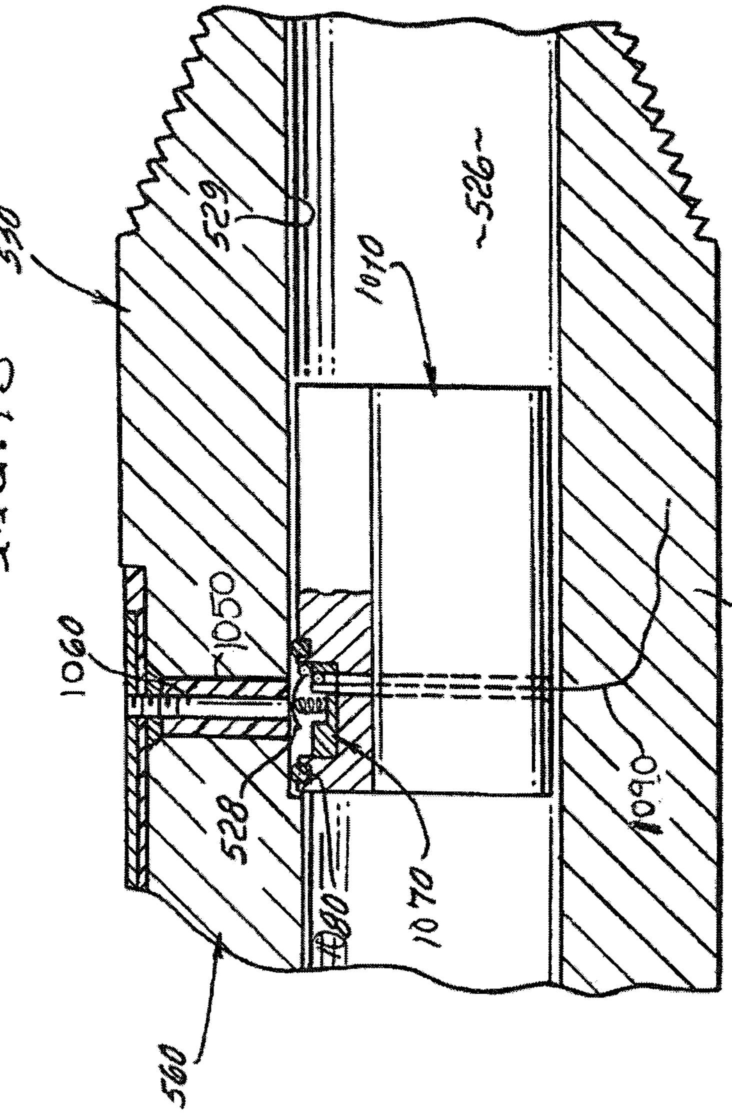
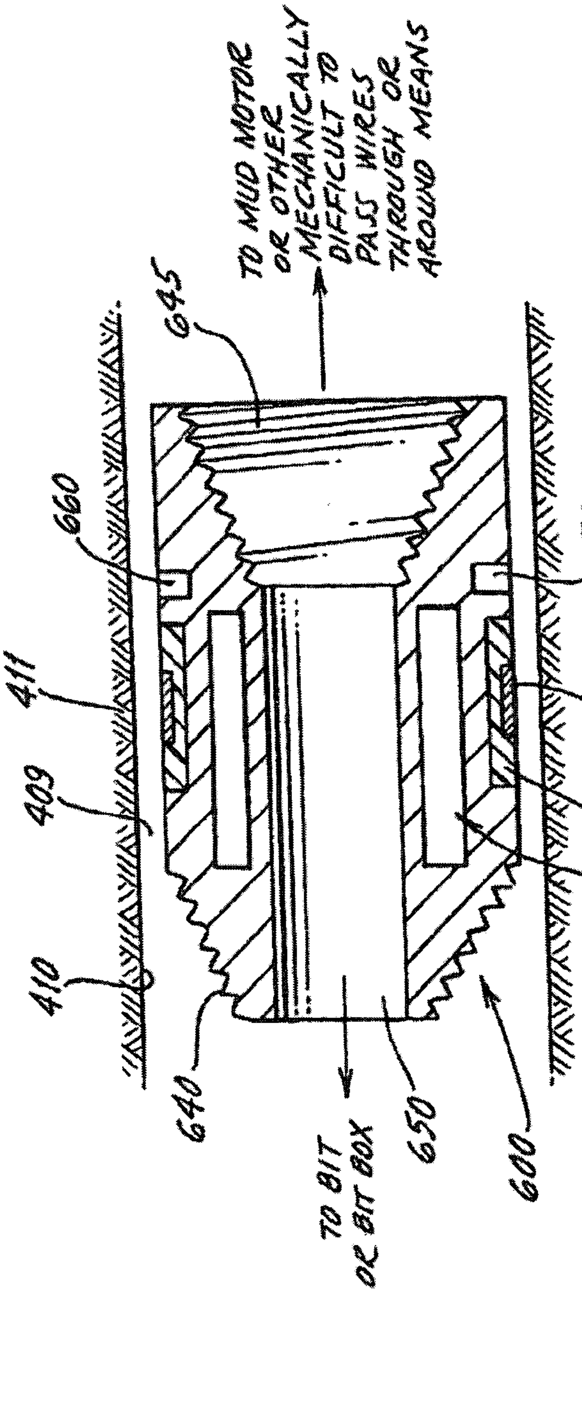


FIG. 7D


TO MUD MOTOR OR OTHER MECHANICALLY DIFFICULT TO PASS WIRES THROUGH OR AROUND MEANS
645
660
670
411
409
410
610
620
630
640
650
600
TO BIT OR BIT BOX

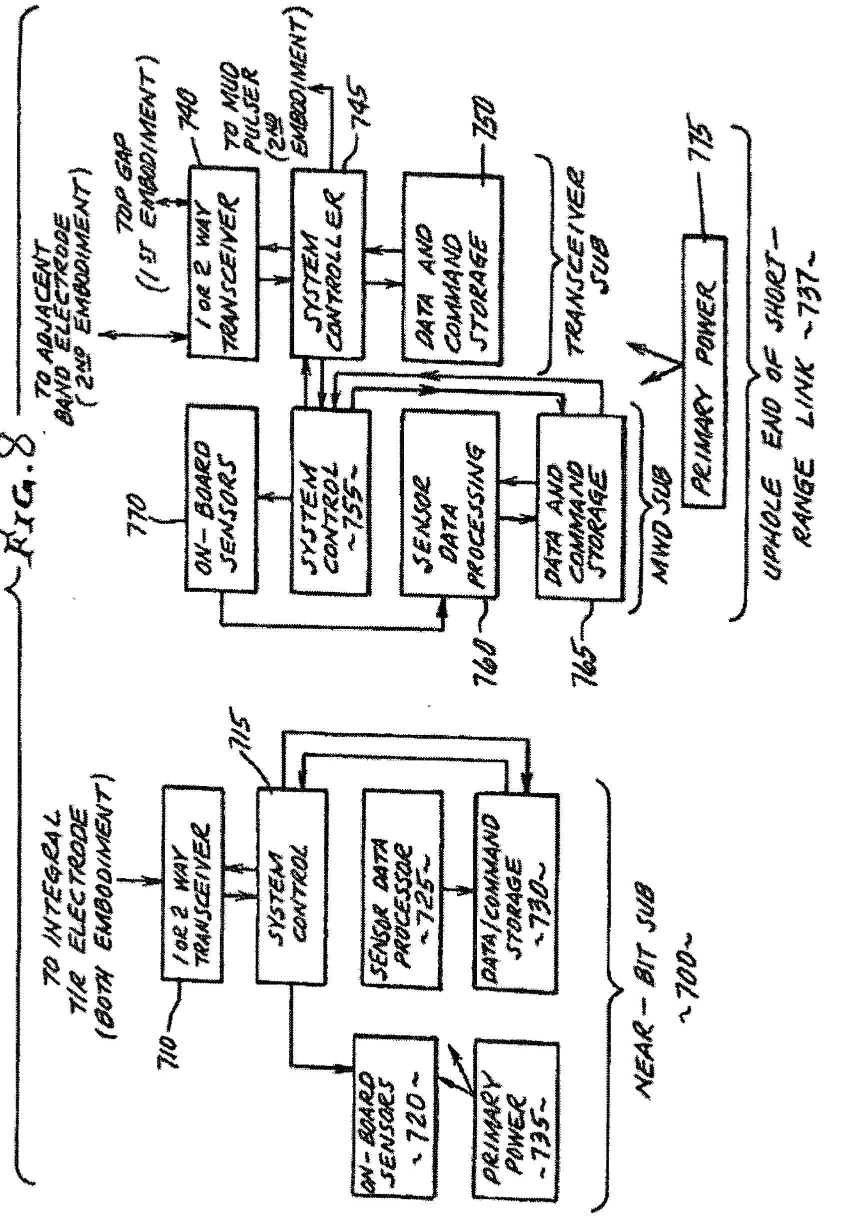

TO ADJACENT BAND ELECTRODE (2ND EMBODIMENT)
TOP GAP (1ST EMBODIMENT)
740
TO MUD PULSER (2ND EMBODIMENT)
745
750
1 OR 2 WAY TRANSCEIVER
SYSTEM CONTROLLER
DATA AND COMMAND STORAGE
TRANSCEIVER SUB
770
ON-BOARD SENSORS
SYSTEM CONTROL ~755~
SENSOR DATA PROCESSING
DATA AND COMMAND STORAGE
MWD SUB
760
765
775
PRIMARY POWER
UPHOLE END OF SHORT-RANGE LINK ~737~
TO INTEGRAL T/R ELECTRODE (BOTH EMBODIMENT)
715
1 OR 2 WAY TRANSCEIVER
SYSTEM CONTROL
SENSOR DATA PROCESSOR ~725~
DATA/COMMAND STORAGE ~730~
710
ON-BOARD SENSORS ~720~
PRIMARY POWER ~735~
NEAR-BIT SUB ~700~

FIG. 8

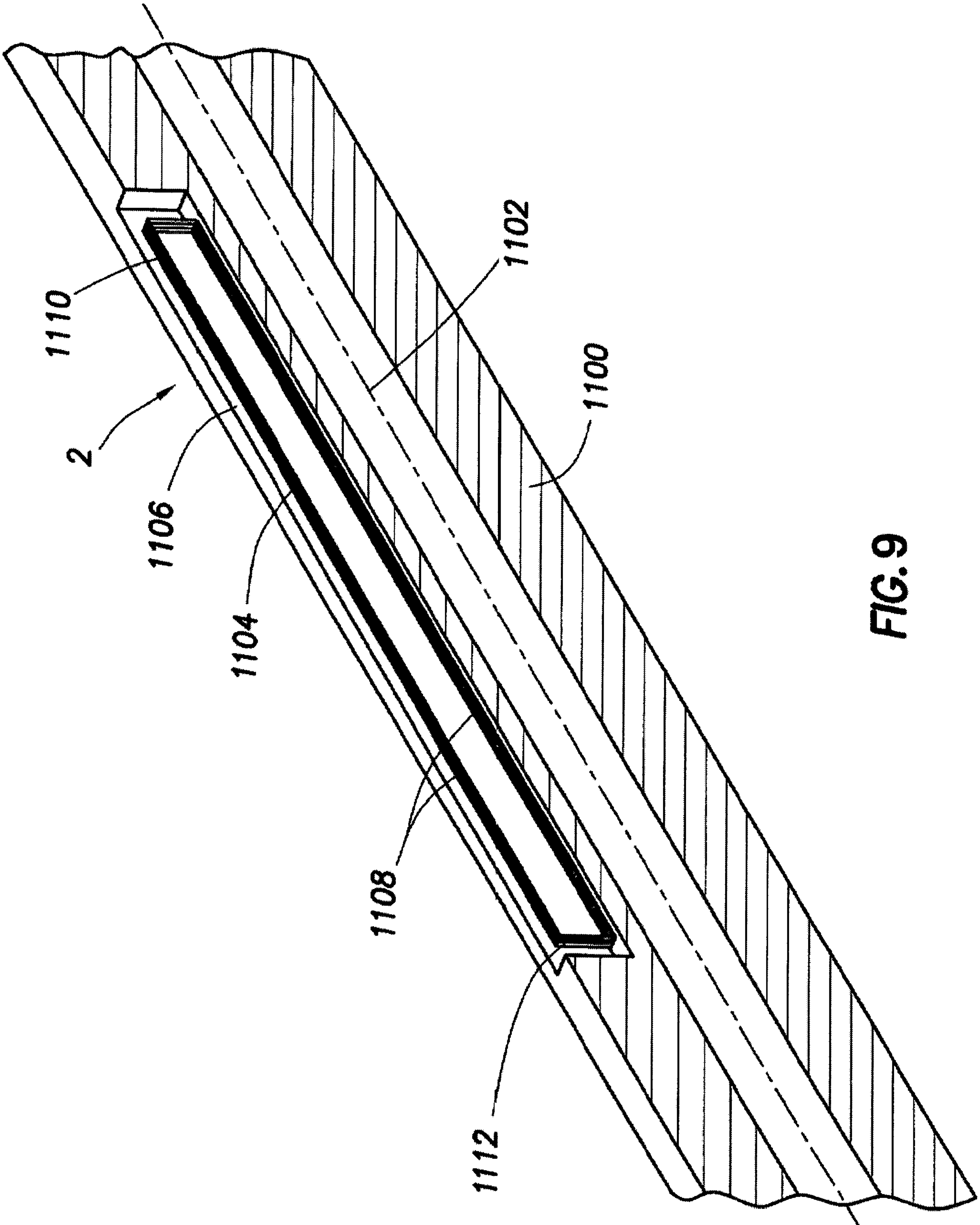


FIG. 9

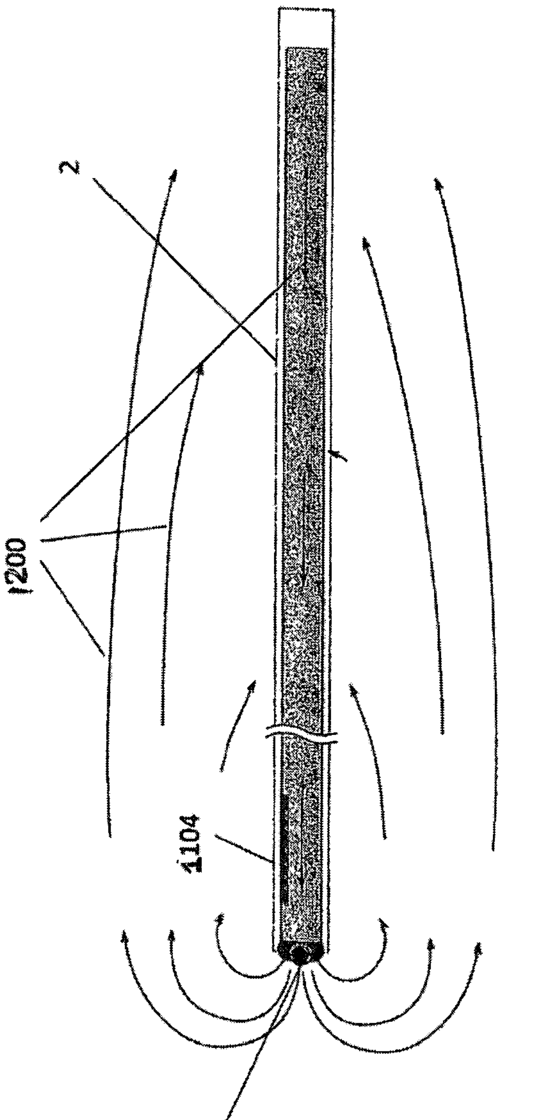


Fig. 10

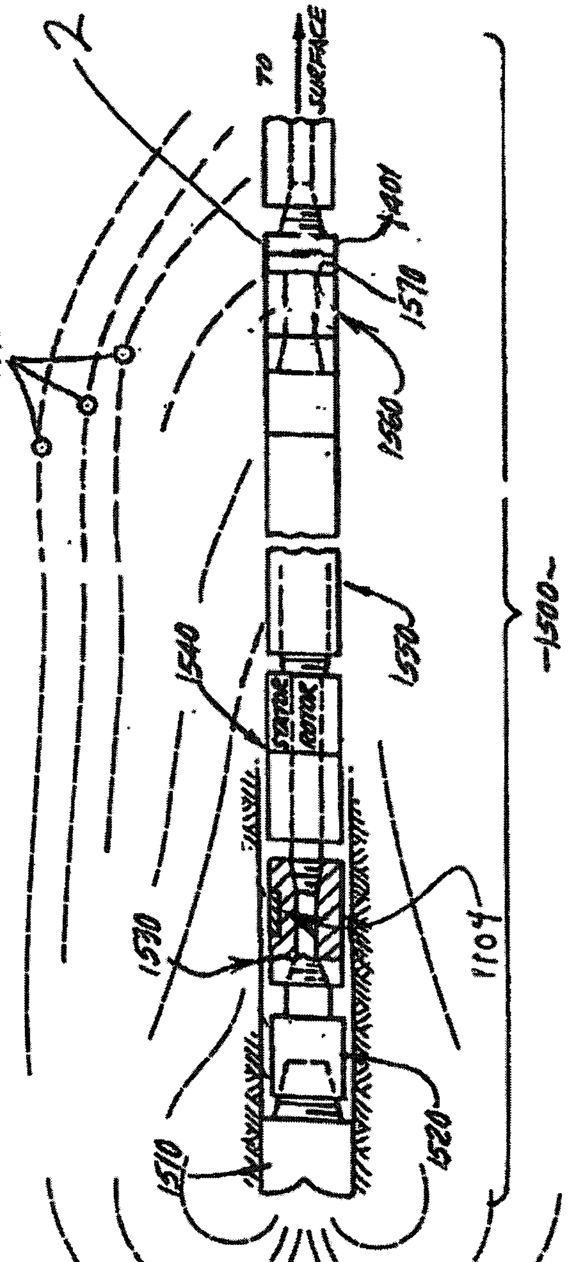

TO SURFACE
2
1200
1401
1570
1560
1550
1540
STATOR
ROTOR
1530
1104
1520
1510
1500

FIG. 11

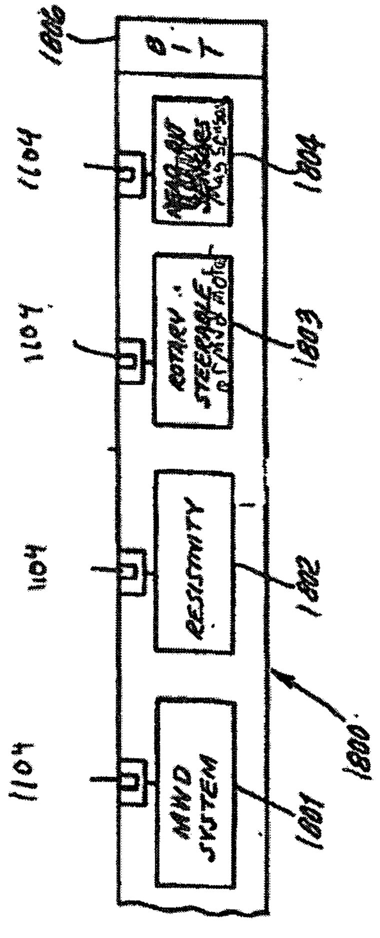

1806
B
I
T
1104
1804
1104
ROTARY
STEERABLE
1803
1104
RESISTIVITY
1802
1104
MWD
SYSTEM
1801
1800

FIG. 12

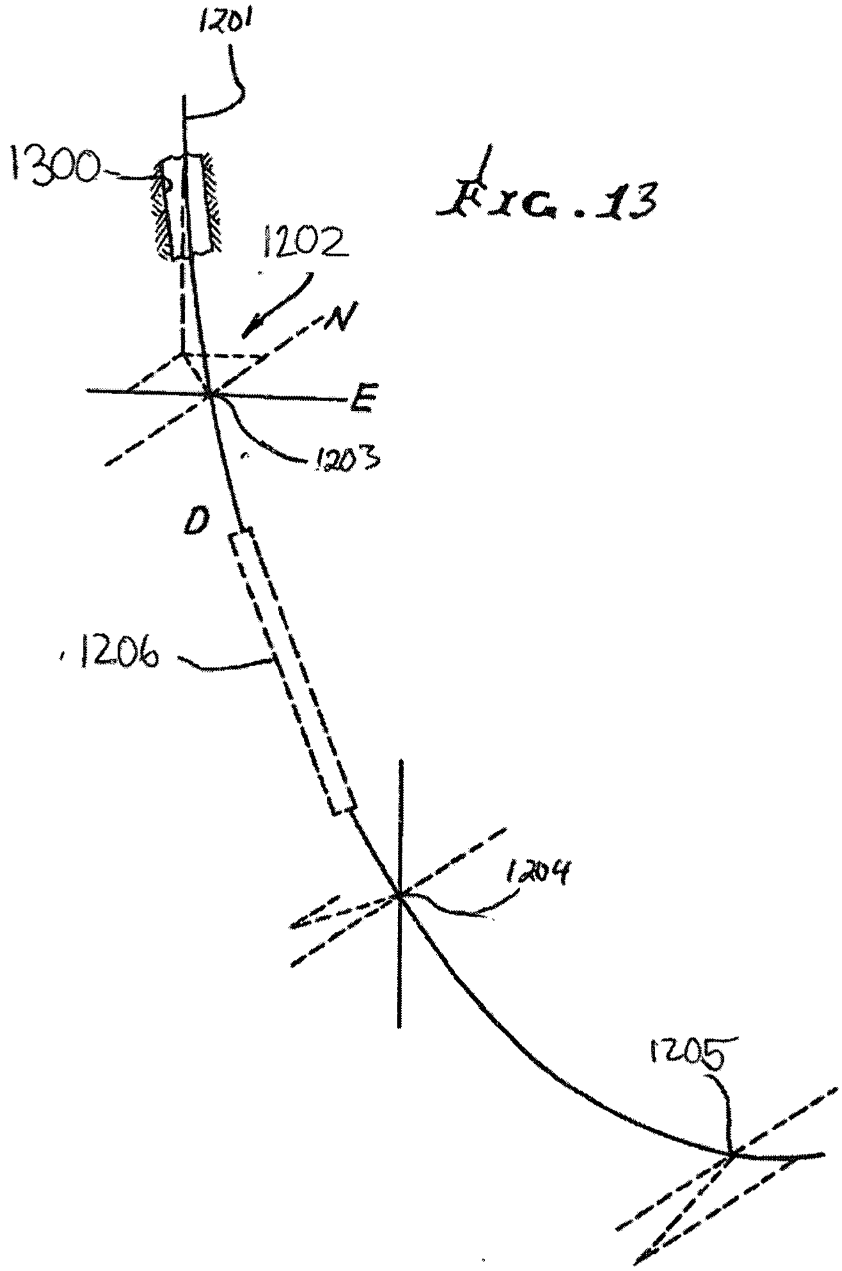
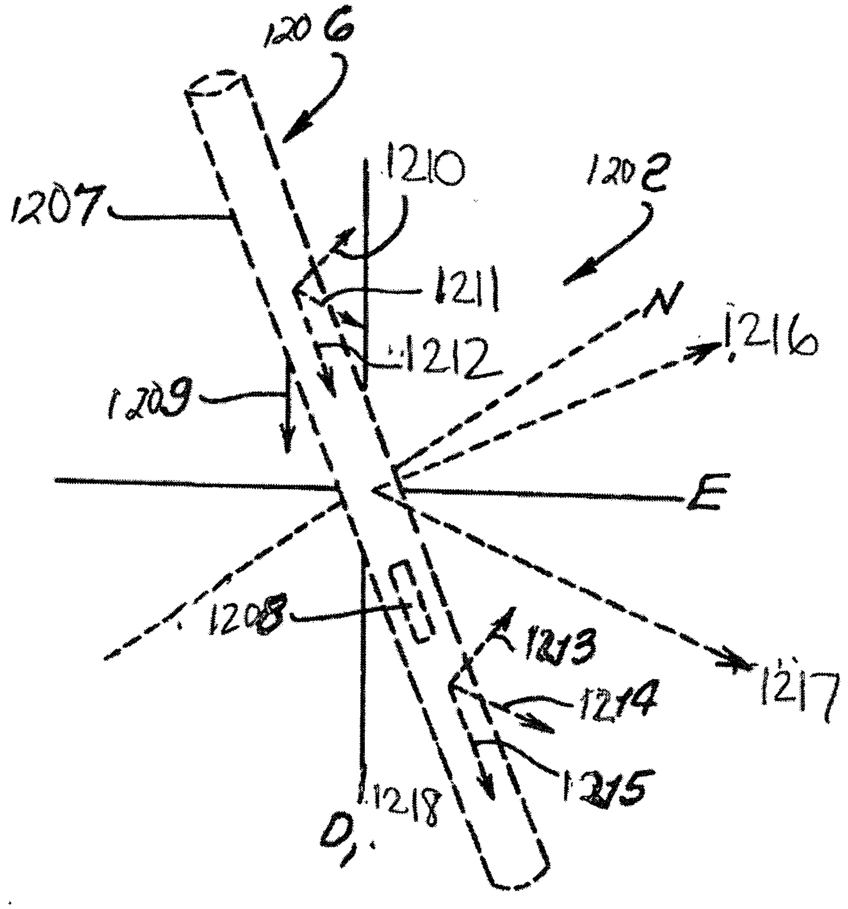


FIG. 13

FIG. 14


1206
1210
1202
1207
1211
N
1216
1212
1209
E
1208
1213
1217
1214
1215
1218
D

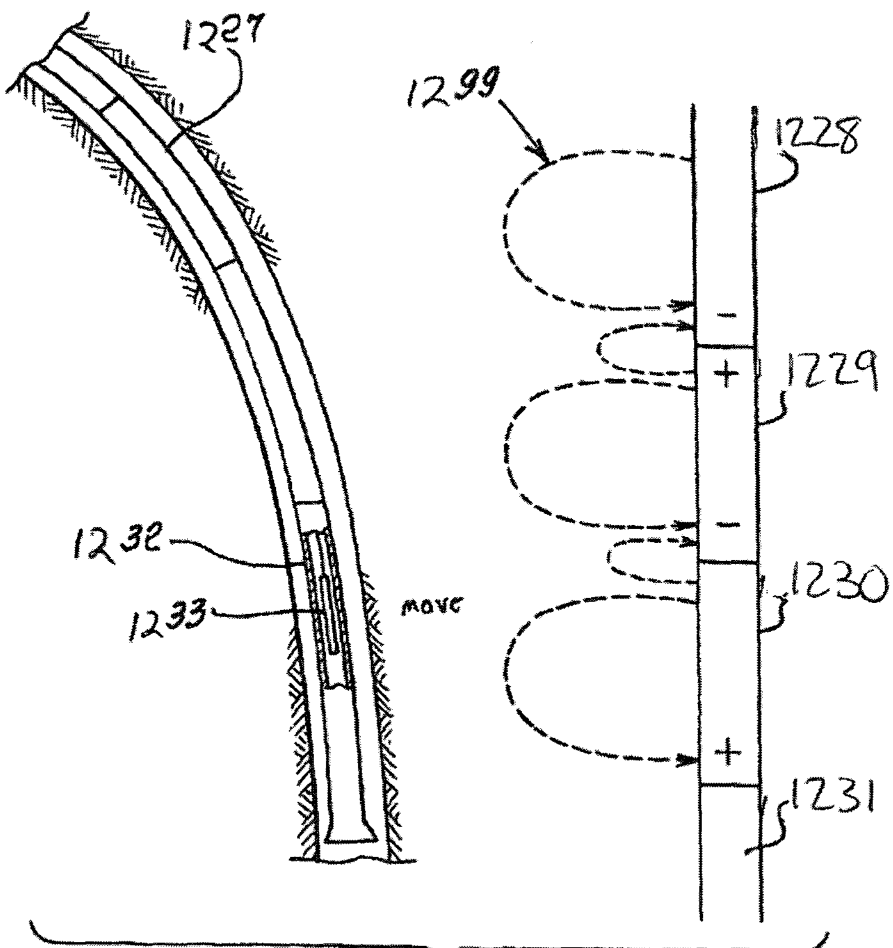


FIG. 15.

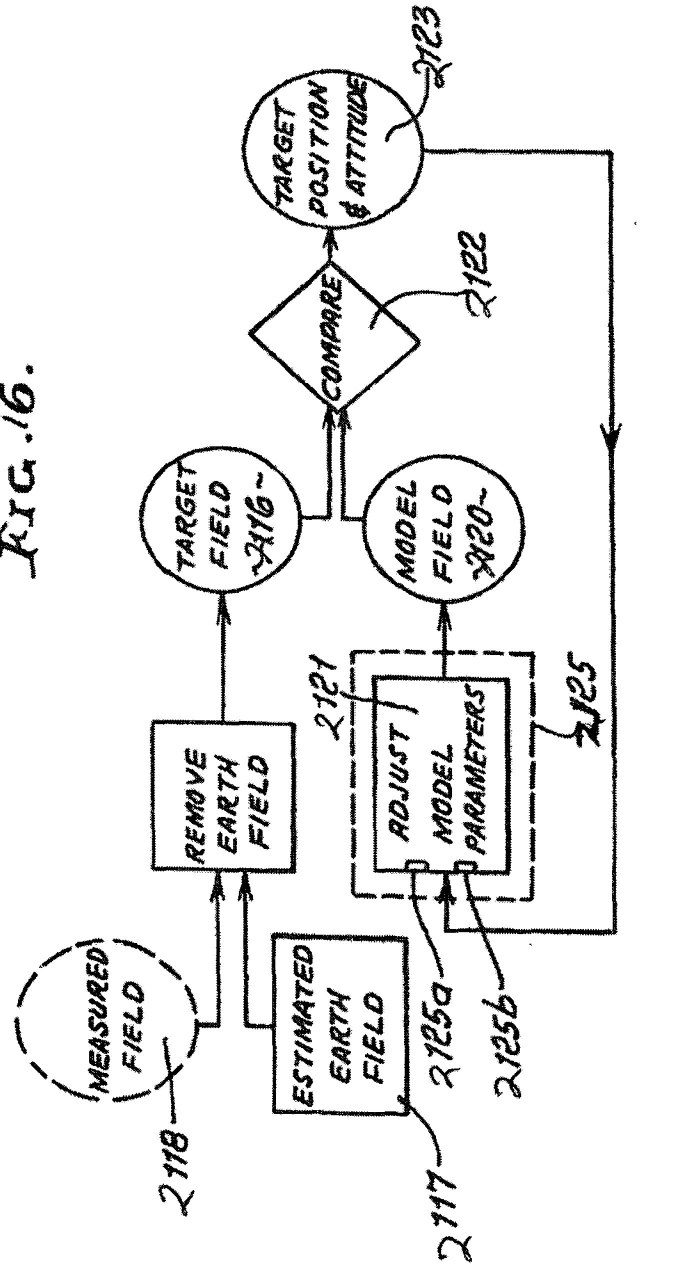

MEASURED FIELD
2118
ESTIMATED EARTH FIELD
2117
REMOVE EARTH FIELD
TARGET FIELD 2116
ADJUST MODEL PARAMETERS
2121
2125
2125a
2125b
MODEL FIELD 2120
COMPARE
2122
TARGET POSITION & ATTITUDE
2123

FIG. 16.

FIG. 17A.

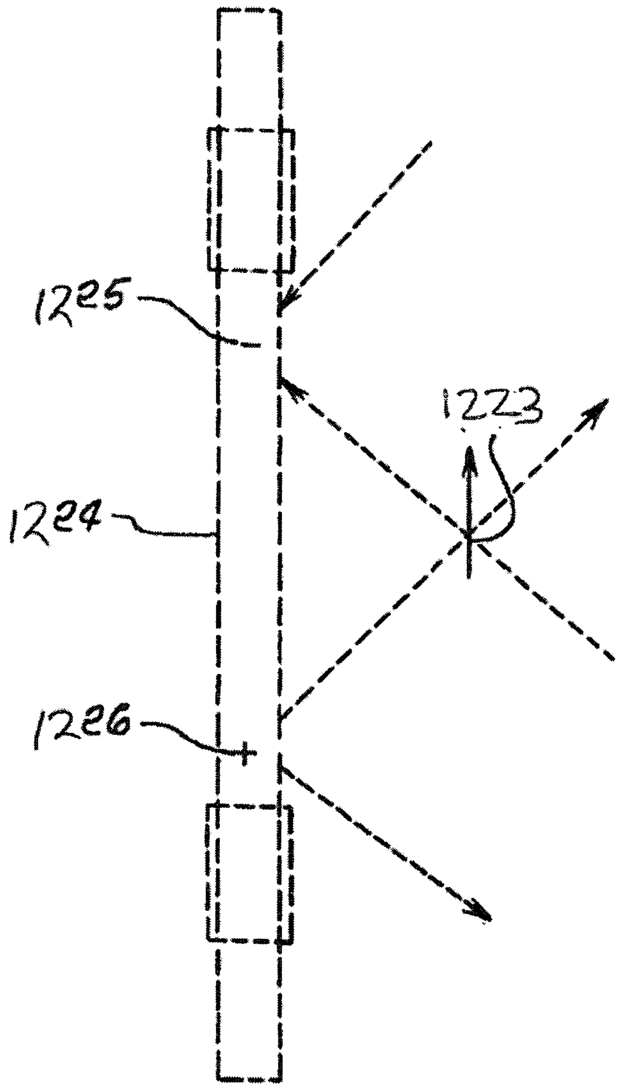
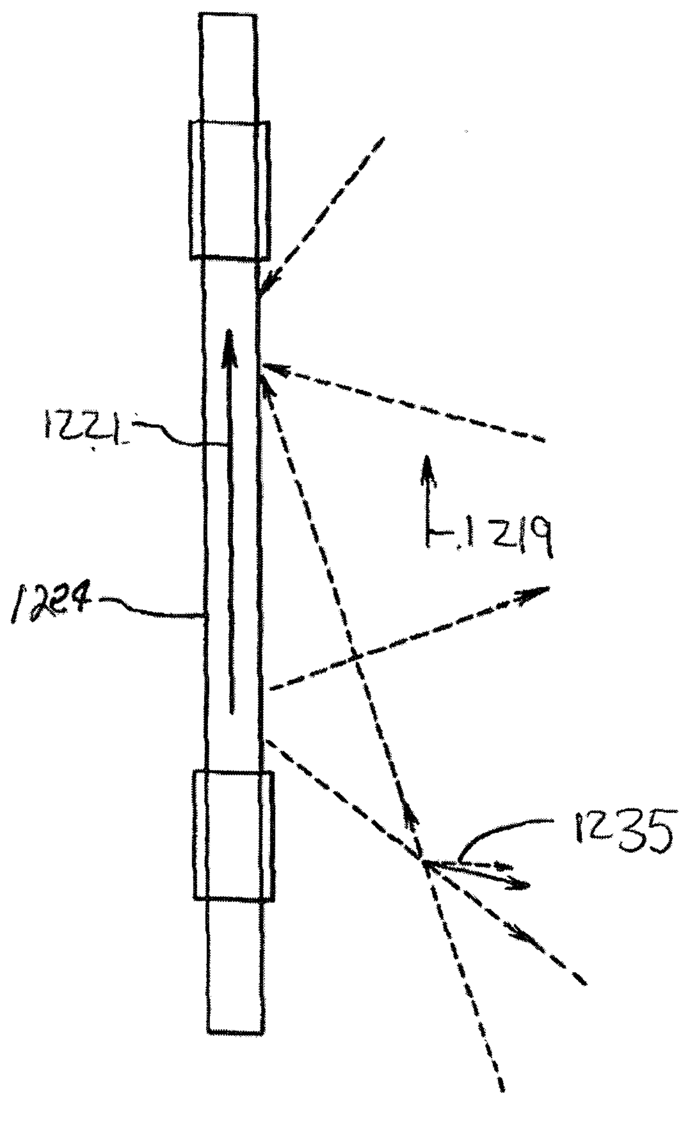


FIG. 17B



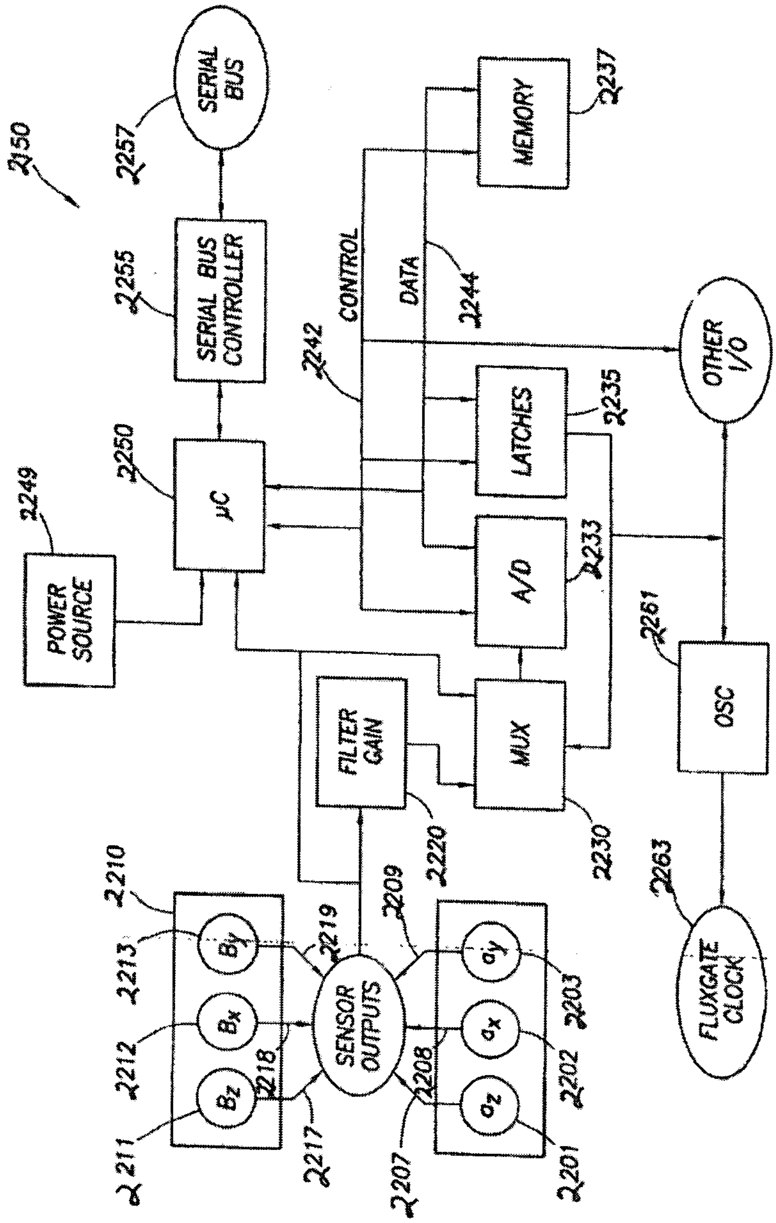

2150
SERIAL BUS
2257
SERIAL BUS CONTROLLER
2255
MEMORY
2237
CONTROL
DATA
2244
2242
OTHER I/O
LATCHES
2235
POWER SOURCE
2249
μC
2250
A/D
2233
2261
OSC
FILTER GAIN
2220
MUX
2230
2263
FLUXGATE CLOCK
2210
B_y
B_x
B_z
2211
2212
2213
SENSOR OUTPUTS
2217
2218
2219
2209
2208
2207
a_y
a_x
a_z
2201
2202
2203

FIG. 18