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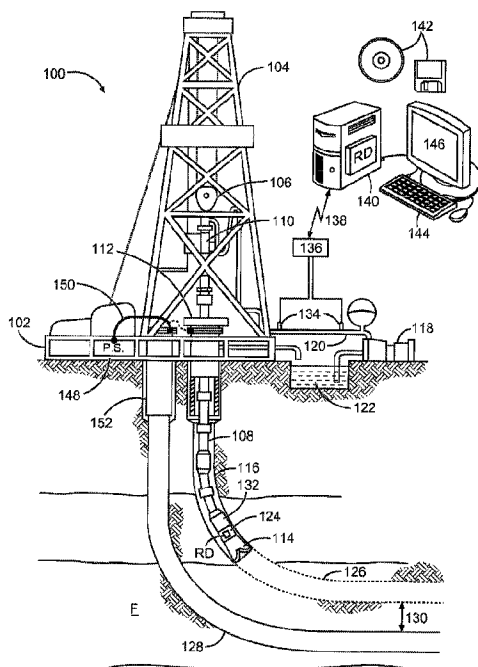
(57) Abrégé/Abstract:
Disclosed embodiments include well ranging apparatus, systems, and methods which operate to receive normal and tangential components of electromagnetic field strength measurements within a first well as a set of field strength components from at least one sensor, wherein the at least one sensor is used to take multiple azimuthal field strength measurements at a single depth. Further activities include determining an approximate range from the at least one sensor to a second well that serves as a source of an electromagnetic field, via direct transmission or backscatter transmission, when a ranging direction associated with a housing upon which the at least one sensor is mounted is unknown. Additional apparatus, systems, and methods are disclosed.

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(54) **Title:** WELL RANGING APPARATUS, SYSTEMS, AND METHODS

(57) **Abstract:** Disclosed embodiments include well ranging apparatus, systems, and methods which operate to receive normal and tangential components of electromagnetic field strength measurements within a first well as a set of field strength components from at least one sensor, wherein the at least one sensor is used to take multiple azimuthal field strength measurements at a single depth. Further activities include determining an approximate range from the at least one sensor to a second well that serves as a source of an electromagnetic field, via direct transmission or backscatter transmission, when a ranging direction associated with a housing upon which the at least one sensor is mounted is unknown. Additional apparatus, systems, and methods are disclosed.

Fig. 1

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WELL RANGING APPARATUS, SYSTEMS, AND METHODS

BACKGROUND

[0002] With much of the world's easily obtainable oil having already been produced, new techniques are being developed to extract less accessible hydrocarbons. These techniques often involve drilling a borehole in close proximity to one or more existing wells. Examples of directed drilling near an existing well include well intersection for blowout control, multiple wells drilled from an offshore platform, and closely spaced wells for geothermal energy recovery. Another such technique is steam-assisted gravity drainage (SAGD) that uses a pair of vertically-spaced, horizontal wells constructed along a substantially parallel path, often less than ten meters apart. Careful control of the spacing contributes to the effectiveness of the SAGD technique.

[0003]   One way to construct a borehole in close proximity to an existing well is "active ranging" or "access-dependent ranging" in which an electromagnetic source is located in the existing well and monitored via sensors on the drill string in the well under construction. Another technique involves systems that locate both the source and the sensor(s) on the drill string – relying on backscatter transmission from the target well to determine the range between the drilling well and the target well. These latter systems are sometimes called "passive ranging" or "access-independent" systems by those of ordinary skill in the art. In either case, the ranging techniques are sometimes limited in the degree of accuracy that can be obtained.

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BRIEF DESCRIPTION OF THE DRAWINGS

[0004]   FIG. 1 depicts an example drilling environment in which ranging embodiments may be employed.

[0005]   FIGs. 2 to 9 illustrate a variety of apparatus, method, and system configurations for various range determination embodiments.

[0006]   FIG. 10 is a block diagram of a wireline system implementation of various embodiments.

[0007]   FIG. 11 is a block diagram of a drilling system implementation of various embodiments.

DETAILED DESCRIPTION

Introduction

[0008]   Magnetic ranging has been widely used for various applications, including well intersection, well avoidance, SAGD, and others. One excitation method for magnetic ranging is surface excitation. Surface excitation is a popular method of generating a ranging signal. It is relatively easy to implement, without the need for complex cabling and equipment. When surface excitation is used, a current is injected into a target well casing at the surface of the well (e.g., at the well head). The current travels along the casing down-hole and generates a magnetic field down-hole that originates from the target via direct transmission, and can be measured at a distance (e.g., in a drilling well) for ranging purposes. As a result, the excitation signal down-hole may be relatively weak when the distance beneath the surface is great, due to the current leakage into the conductive formation. Consequently, sensor noise often affects magnetic ranging accuracy at greater depths, leading to false signal measurements and failures in well location. Some of the embodiments described herein are designed to improve down-hole current strength and/or enhance the signal/noise ratio, for improved accuracy with respect to ranging measurement technology.

[0009]   Such apparatus, methods, and systems can be even more useful when backscatter ranging is used: that is, when the excitation source is injected into the casing of the drilling well, or is attached to a drill string within the drilling well. In the case of backscatter ranging, the excitation source originates a direct transmission signal that impinges upon, and is

then reflected from, the target well. When these backscatter transmission signals are received at a receiver in the drilling well, the resulting received ranging signals are even weaker than in the direct transmission case.

[0010]   Thus, novel apparatus, methods, and systems are proposed to
5   increase the strength of the received ranging signal, to improve the received signal-to-noise ratio (SNR), and to improve the accuracy of ranging signal measurements. In some embodiments, enhancements are realized in all three of these areas. By taking this approach, ranging system technology can be improved in a number of ways, via improved accuracy and reliability of
10   individual ranging measurements. Therefore, the apparatus, methods, and systems proposed herein can be used to reduce measurement issues that arise due to noise, as well as to generate larger signals at great depths. The result is that the maximum detection ranges for existing ranging systems can be significantly improved. In some embodiments, the apparatus, methods,
15   and systems described herein can be applied to electromagnetic (EM) telemetry applications.

[0011]   FIG. 1 depicts an example drilling environment 100 in which ranging embodiments may be employed. The disclosed apparatus (e.g., logging tools), systems, and methods are best understood in the context of
20   the larger systems in which they operate. Accordingly, FIG. 1 illustrates an example drilling environment 100 in which a drilling platform 102 supports a derrick 104 having a traveling block 106 for raising and lowering a drill string 108. A top drive 110 supports and rotates the drill string 108 as it is lowered through the well-head 112. A drill bit 114 is driven by a downhole
25   motor and/or rotation of the drill string 108. As the drill bit 114 rotates, it creates a borehole 116 that passes through various formations F. A pump 118 circulates drilling fluid through a feed pipe 120 to top drive 110, downhole through the interior of drill string 108, through orifices in drill bit 114, back to the surface via the annulus around drill string 108, and into a
30   retention pit 122. The drilling fluid transports cuttings from the borehole into the retention pit 122 and aids in maintaining the borehole integrity.

[0012]   The drill bit 114 is just one piece of a bottom-hole assembly (BHA) that includes one or more drill collars (comprising thick-walled steel pipe) to provide weight and rigidity to aid the drilling process. Some of

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these drill collars include logging instruments to gather measurements of

various drilling parameters such as position, orientation, weight-on-bit,

borehole diameter, etc. The tool orientation may be specified in terms of a

tool face angle (also known as rotational or azimuthal orientation), an

5   inclination angle (the slope), and a compass direction, each of which can be

derived from measurements made by magnetometers, inclinometers, and/or

accelerometers, though other sensor types such as gyroscopes may also be

used. In one specific embodiment, the tool includes a three-axis fluxgate

magnetometer and a three-axis accelerometer. As is known in the art, the

10   combination of these two sensor systems enables the measurement of the

tool face angle, inclination angle, and compass direction. In some

embodiments, the tool face and hole inclination angles are calculated from

the accelerometer sensor output, and the magnetometer sensor outputs are

used to calculate the compass direction.

15   **[0013]**   The BHA further includes a ranging tool 124 to receive signals from

current injected by a power supply 148 into nearby conductors such as pipes,

casing strings, and conductive formations and to collect measurements of the

resulting field to determine distance and direction. Using measurements of these

signals, in combination with the tool orientation measurements, the driller can,

20   for example, steer the drill bit 114 along a desired path in the drilling well 126

relative to the existing well (e.g., target well) 128 in formation F using any one

of various suitable directional drilling systems, including steering vanes, a "bent

sub", and a rotary steerable system. For precision steering, the steering vanes

may be the most useful steering mechanism. The steering mechanism can be

25   controlled from the Earth's surface, or downhole, with a downhole controller

programmed to follow the existing borehole 128 at a predetermined distance 130

and position (e.g., directly above or below the existing borehole).

[0014]   The ranging tool 124 may comprise one or more elements,

interchangeably designated as receivers or sensors in this document. These

30   elements may comprise uniaxial, biaxial, or triaxial magnetometers, coil

antennas, and/or telemetry receivers.

[0015]   A telemetry sub 132 coupled to the downhole tools (including

ranging tool 124) transmits telemetry data to the surface via mud pulse

telemetry. A transmitter in the telemetry sub 132 modulates a resistance to

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drilling fluid flow to generate pressure pulses that propagate along the fluid

stream at the speed of sound to the surface. One or more pressure

transducers 134 convert the pressure signal into electrical signal(s) for a

signal digitizer 136. Note that other forms of telemetry exist and may be

5   used to communicate signals from downhole to the digitizer. Such telemetry

may include acoustic telemetry, electromagnetic telemetry, or telemetry via

wired drill pipe.

[0016]   The digitizer 136 supplies a digital form of the telemetry signals via a

communications link 138 to a computer 140 or some other form of a data

10   processing device. The computer 140 operates in accordance with software

(which may be stored on non-transitory information storage media 142) and user

input provided via an input device 144 to process and decode the received

signals. The resulting telemetry data may be further analyzed and processed by

the computer 140 to generate a display of useful information on a computer

15   monitor 146 or some other form of a display device. For example, a driller could

employ this system to obtain and monitor drilling parameters, formation

properties, and the path of the borehole relative to the existing borehole 128 and

any detected formation boundaries. A downlink channel can then be used to

transmit steering commands from the surface to the BHA. In some embodiments,

20   the computer 140 has analog circuitry installed or is programmed to include a

ranging determination module RD, which operates on the signal data received

down hole at the ranging tool 124 to determine the distance and direction from

the drilling well 126 to the target well 128. The ranging determination module

RD may exist in the computer 140 or the tool 124, and may be used to

25   implement any of the methods described herein.

[0017]   Thus, FIG. 1 illustrates an electromagnetic ranging system with

surface excitation. The power supply 148 at the surface employs a cable 150

to inject current into target well casing 152 and flowing down-hole so that

magnetic fields can be generated surrounding a target well 128. Then

30   sensors in the ranging tool 124 in the drilling well 126 can determine the

magnetic field strength in various directions so that distance and direction

between the target well 128 and drilling well 126 can be determined. The

power supply 148 can also be connected to inject current into the casing of

the drilling well 126, or be disposed downhole in either the drilling well 126 (shown) or the target well 128 (not shown in this figure).

[0018]   The drilling well 126 and the target well 128 are often constructed as a cased hole, with cement installed around the outside of the

5   casing material (e.g., conductive piping). In the completion phase of oil and gas wells, the cement serves to isolate the wellbore, helps prevent casing failure, and keeps the wellbore fluids from contaminating freshwater aquifers.

[0019]   When conventional ranging systems are used in a two-sensor

10   ranging configuration, with the sensors located in the same azimuthal plane, the tool may go through a variety of spatial orientations, and as a result, the tool face angle may not be known. Thus, it may be difficult to determine the range between wells, which comprises the ranging distance and the ranging direction.

15   [0020]   As a solution to this technical problem, the inventors have developed a variety of apparatus, systems, and methods. These will be explained in the context of apparatus, systems, and methods that operate to process gradient field measurements from two or more separated sensors. These measurements may be used to determine the relative distance

20   between the tool center and a target line source, such as the approximate range between a drilling well and a target well. Thus, the apparatus, methods, and systems described herein are applicable to magnetic ranging applications, including steam-assisted gravity drainage (SAGD) application, well avoidance, and well interception operations. The result of

25   implementing various embodiments may be improved accuracy. Several embodiments that may provide some of these advantages will now be described.

Detailed Presentation

[0021]   In some embodiments, when the ranging direction is not known,

30   a set of two sensors, such as magnetometers, can be rotated by a selected number of degrees in the azimuthal direction (e.g., 10, 20, 30, 40, 50, 60, 70, 80, or 90 degrees, or more), where the number of degrees of rotation corresponds to the applied methodology, to gain additional measurement information. In some embodiments, an additional sensor is provided, and

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located some number of degrees away from the original sensor(s) in the azimuthal direction. The additional information provided by the rotated sensors (or one or more additional sensors) can be used to determine the range between wells, without knowing the angle Theta Θ to the target well.

5   For example, the number of degrees for rotation can be selected to provide a threshold gradient field magnitude, given the magnitude of the measured field strength signals from one or more sensors in one or more azimuthal locations. The number of degrees for rotation can also be selected to provide a threshold gradient field magnitude above a determined noise level, which

10   can be determined using each of the sensors, as will become apparent to those of ordinary skill in the art after reading the content of this disclosure.

[0022]   In some embodiments, apparatus, systems, and methods use two sensors (e.g., magnetometers) to measure the gradient field, where the two sensors are attached to a logging tool and separated by a known distance.

15   The processing methods described herein may be based on (1) total field measurement, (2) the tangential field component, and/or (3) the normal field component of the sensor measurements to determine the range distance R between wells, even when the ranging direction is unknown. These methods can be applied to three or more sensors. In many embodiments, the vector

20   sum of the normal component and the tangential component and/or the longitudinal component provides the total field component.

Initial Calculations to Determine Range

[0023]   FIGs. 2 to 9 illustrate a variety of apparatus, method, and system configurations for various range determination embodiments. To begin, the

25   reader is referred to FIG. 2, which shows the magnetic field H for an infinite line source 200 characterized by a constant current *I*. Based on Ampere's law, the magnetic field H at low frequency surrounding the line source 200 may be expressed as:

30
$$\bar{H} = \frac{I}{2\pi r}\hat{\Phi}, \qquad (1)$$

where r is the distance between a measurement point and the infinite line source 200. In addition, the gradient field can be given by

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$$\frac{\partial \vec{H}}{\partial r} = -\frac{I}{2\pi r^2}\hat{\Phi} . \qquad (2)$$

5   **[0024]**   Consequently, the distance r can be directly computed by taking the ratio of the amplitude of Equation (1) to the amplitude of Equation (2), given by:

$$\left|\frac{\vec{H}}{\dfrac{\partial \vec{H}}{\partial r}}\right| = \left|\frac{\dfrac{I}{2\pi r}}{\dfrac{-I}{2\pi r^2}}\right| = r . \qquad (3)$$

10

[0025]   Equation (3) may be designated as the gradient method to compute a ranging distance. In practice, two sensors (e.g., magnetometers) may be used to compute magnetic field and gradient field measurements, as shown in FIG. 3, which presents diagram of an infinite line source 300 and a

15   logging tool 310 equipped with two sensors S1, S2 for gradient field determination.

[0026]   A finite difference method can be utilized to calculate the magnetic field strength H and the gradient field strength, as given by

$$\vec{H} = \frac{\vec{H}_1 + \vec{H}_2}{2} , \text{ and} \qquad (4a)$$

20

$$\frac{\partial \vec{H}}{\partial r} = \frac{\vec{H}_1 - \vec{H}_2}{2\Delta S} , \qquad (4b)$$

where H_1 and H_2 are the total field measurements at sensors S1 and S2, respectively. ΔS is the separation between each sensor and the tool center.

Consequently, Equation (3) can be modified based on the finite difference method to compute the ranging distance r as

$$r = \left| \frac{\left| \frac{\vec{H}_1 + \vec{H}_2}{2} \right|}{\left| \frac{\vec{H}_1 - \vec{H}_2}{2\Delta S} \right|} \right|. \qquad (5)$$

[0027]   However, as part of operations in the field, the location of the tool face varies while drilling. The tool face is the angle between a fixed reference point on a down hole tool and either the high side of the tool in the well, or magnetic North, and may be designated arbitrarily. Related to the tool face is the ranging direction, which may be designated as the angle theta θ in FIG. 3. If sensor S1 does not lie on a straight line R between the line source point and the tool center (meaning the ranging direction θ shown in the figure is not zero), then Equations (4) and (5) are not valid. The value of the ranging direction θ will affect the value of total field strength and direction measurements. Without taking this ranging direction θ into consideration, conventional gradient calculations may fail to provide an accurate ranging distance.

Processing Methods based on Total Field Measurements

[0028]   To adjust the effects of the change in the ranging direction θ, ranging calculations based on total field measurements of each sensor will be considered. For this discussion, each sensor is assumed to measure three orthogonal field components to acquire a total field measurement. The three orthogonal field components are: the normal component, the tangential component, and the z component shown for the downhole tool housing 400 in FIG. 4.

[0029]   In FIG. 4, the normal component and the tangential component are in the tool azimuthal plane. The direction of the tangential component is in the tool rotation direction, whereas the normal direction that is perpendicular to tool rotation points away from the tool center and lies on a straight line between the tool center and the location of Sensor 1. The

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longitudinal z component is parallel to the tool mandrel along with the

BHA. Thus, the z component is parallel to the longitudinal axis of the tool.

[0030]   For simplicity in the calculations that follow, the sensors S1 and

S2 are oriented 180° away from each other, attached to a housing 500, such

5   as a logging tool, as shown in FIG. 5, and are utilized to determine the

ranging distance R. ΔS represents the separation between each of the sensors

and the tool center, such that the sensors S1 and S2 are separated by a

distance of $2\Delta S$. Therefore, the total field measured at sensor S1 can be

expressed as

10

$$H_1 = \frac{I}{2\pi R_1} = \frac{I}{2\pi\sqrt{R^2 + \Delta S^2 + 2R\Delta S \cos\theta}}, \qquad (6)$$

whereas the total field measured at sensor S2 is given by

15     $$H_2 = \frac{I}{2\pi R_2} = \frac{I}{2\pi\sqrt{R^2 + \Delta S^2 - 2R\Delta S \cos\theta}}, \qquad (7)$$

where

$$R_1 = \sqrt{R^2 + \Delta S^2 + 2R\Delta S \cos\theta}, \text{ and} \qquad (8)$$

20

$$R_2 = \sqrt{R^2 + \Delta S^2 - 2R\Delta S \cos\theta}. \qquad (9)$$

[0031]   Using the finite difference method, Equations (4a) and (4b) can

be modified as shown, to produce Equations (10) and (11) below,

25   respectively:

$$H = \frac{H_1 + H_2}{2} = \frac{I}{4\pi}\left(\frac{1}{R_1} + \frac{1}{R_2}\right) = \frac{I}{4\pi R_1 R_2}(R_1 + R_2), \text{ and} \qquad (10)$$

$$\frac{\partial H}{\partial r} = \frac{\Delta H}{2\Delta S} = \frac{H_1 - H_2}{2\Delta S} = \frac{I}{4\pi\Delta S}\left(\frac{1}{R_1} - \frac{1}{R_2}\right) = \frac{I}{4\pi\Delta S R_1 R_2}(R_2 - R_1)$$

.   (11)

[0032]   Then, taking the ratio of Equation (10) to Equation (11) gives:

$$\frac{H}{\frac{\Delta H}{2\Delta S}} = \frac{\frac{H_1 + H_2}{2}}{\frac{H_1 - H_2}{2\Delta S}} = \Delta S \frac{(R_1 + R_2)}{(R_2 - R_1)} = \Delta S \frac{R_1^2 + R_2^2 + 2R_1 R_2}{R_2^2 - R_1^2} . \quad (12)$$

[0033]   Applying Equations (8) and (9) to simplify the expression of Equation (12) renders Equation (13) as:

$$\frac{\frac{H_1 + H_2}{2}}{\frac{H_1 - H_2}{2\Delta S}} = \frac{R}{-2\cos\theta}\left(1 + (\frac{\Delta S}{R})^2 + \sqrt{1 + (\frac{\Delta S}{R})^4 - 2(\frac{\Delta S}{R})^2 \cos(2\theta)}\right) .$$

(13)

[0034]   The left side of Equation (13) can be calculated based on the measurements of H_1 and H_2 and the known distance ΔS. The right side of Equation (13) has two unknown parameters: the ranging direction θ and the ranging distance R. However, the ranging direction θ can be calculated when each sensor operates to acquire both tangential and normal components of the magnetic field. Consequently, the ranging distance R can be directly computed from Equation (13) when the ranging direction θ is known.

[0035]   Generally speaking, the sensor separation for a down hole tool is much smaller than the ranging distance to be measured, indicating that the value of the ratio $\frac{\Delta S}{R}$ is much smaller than 1. Taking this fact into account, Equation (13) can often be simplified as:

$$\frac{H}{\frac{\Delta H}{2\Delta S}} - \frac{\frac{H_1 + H_2}{2}}{\frac{H_1 - H_2}{2\Delta S}} \approx \frac{R}{-\cos\theta} . \quad (14)$$

[0036]   For the following discussion, two sensors (sensor S1 and S2 in FIG. 5) are designated as the first pair of gradient sensors. If a logging tool is equipped with a second pair of gradient sensors that are azimuthally oriented 90 degrees away from the first pair (as shown for sensors S3, S4 in FIG. 5, such that $\theta \rightarrow \theta + 90°$ in FIG. 3), then the second pair of gradient sensors will be able to obtain a measurement illustrated by Equation (15), as follows:

$$\frac{H}{\frac{\Delta H}{2\Delta S}}_{Pair2} \approx \frac{R}{\sin\theta}. \tag{15}$$

[0037]   Therefore, Equation (16) can be used to directly calculate the ranging distance R without taking the ranging direction θ into consideration:

$$\sqrt{\frac{1}{\left(\frac{\frac{\Delta H}{2\Delta S}}{H}\right)^2_{Pair1} + \left(\frac{\frac{\Delta H}{2\Delta S}}{H}\right)^2_{Pair2}}} = \sqrt{\frac{1}{\frac{\cos^2\theta}{R^2} + \frac{\sin^2\theta}{R^2}}} = R \tag{16}$$

Of course, the ranging direction θ can be also determined by taking the ratio between Equations (14) and (15), as noted previously.

[0038]   In some embodiments, the second pair of gradient sensors (sensors S3 and S4) are not physically installed in the logging tool to enable the use of Equation (16). Instead, owing to the conditions surrounding logging while drilling (LWD) or measurement while drilling (MWD) services, sensors S1 and S2 can be used to make stationary measurements at a first tool azimuth angle, and then, once the tool is rotated by 90 degrees (or some other angle) away from the first tool azimuth angle, a second set of stationary measurements can be made – which is the equivalent of taking measurements with a second pair of sensors S3, S4. The two sets of

measurements taken at two different tool azimuth angles that are separated by 90 degrees (or some other angle) will also enable the use of Equation (16), without the use of four physical sensors.

Processing Methods based on Tangential Component Measurements

5   **[0039]**   Instead of using the total field measurements discussed previously, one can determine a solution that uses only using tangential component measurements to provide a ranging distance calculation. For example, FIG. 6 presents an infinite line source 600 and a tool housing 610, such as a logging tool, equipped with two sensors S1, S2 for tangential field

10   determination. H_{x1} and H_{x2} indicate the tangential component received at sensors S1 and S2, respectively. R_1 and R_2 are the shortest distances between the line source and sensors S1 and S2, respectively.

[0040]   Therefore, H_{x1} and H_{x2} can be expressed as

$$H_{x1} = H_1 \cos(\theta - \alpha_1) =$$

15   $$\frac{I}{2\pi R_1}(\cos\theta\cos\alpha_1 + \sin\theta\sin\alpha_1) = \frac{I}{2\pi R_1^2}(R\cos\theta + \Delta S)\text{,}$$

and   (17a)

$$H_{x2} = -H_2\cos(\theta + \alpha_2) =$$

$$\frac{-I}{2\pi R_2}(\cos\theta\cos\alpha_2 - \sin\theta\sin\alpha_2) = \frac{-I}{2\pi R_2^2}(R\cos\theta - \Delta S)\text{,}$$

(17b)

20   where

$$\cos\alpha_1 = \frac{R + \Delta S\cos\theta}{R_1},$$ (18a)

25   $$\sin\alpha_1 = \frac{\Delta S\sin\theta}{R_1},$$ (18b)

$$\cos\alpha_2 = \frac{R - \Delta S\cos\theta}{R_2},$$ (18c)

$$\sin\alpha_2 = \frac{\Delta S \sin\theta}{R_2},\qquad\qquad(18d)$$

$$R_1^2 = (R + \Delta S \cos\theta)^2 + (\Delta S \sin\theta)^2 = R^2 + \Delta S^2 + 2R\Delta S \cos\theta \qquad(19a)$$

, and

$$R_2^2 = (R - \Delta S \cos\theta)^2 + (\Delta S \sin\theta)^2 = R^2 + \Delta S^2 - 2R\Delta S \cos\theta \qquad(19b)$$

[0041]   As was accomplished with respect to Equations (10) and (11) above, Equations (20) and (21) can be calculated based on tangential components as:

$$H = \frac{H_{x1} - H_{x2}}{2} = \frac{I}{4\pi R_1^2 R_2^2}[R\cos\theta(R_1^2 + R_2^2) + \Delta S(-R_1^2 + R_2^2)] =$$

$$\frac{IR\cos\theta}{2\pi R_1^2 R_2^2}(R^2 - \Delta S^2)\text{, and}\qquad\qquad(20)$$

$$\frac{\Delta H}{2\Delta S} = \frac{H_{x1} + H_{x2}}{2\Delta S} = \frac{I}{4\pi\Delta S R_1^2 R_2^2}[R\cos\theta(-R_1^2 + R_2^2) + \Delta S(R_1^2 + R_2^2)] =$$

$$\frac{-I}{2\pi R_1^2 R_2^2}(R^2\cos 2\theta - \Delta S^2)\qquad\qquad(21)$$

[0042]   At this point, Equation (22) can be obtained by taking the ratio of Equation (20) to Equation (21), as:

$$\frac{H}{\frac{\Delta H}{2\Delta S}} = \frac{R\cos\theta(R^2 - \Delta S^2)}{-(R^2\cos 2\theta - \Delta S^2)}.\qquad\qquad(22)$$

[0043]   From Equation (22), the ranging distance R can be calculated based on the tangential component measurements of H and ΔH, the calculated angle θ, and the known separation of ΔS. However, it is noted that in this case both tangential and normal components at each sensor are

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used to calculate the ranging direction θ. To avoid the use of the ranging

direction θ in the calculation, a second pair of gradient sensors (e.g., sensors

S3, S4) is utilized to provide measurements, to obtain an answer from

Equation (23), as:

5

$$\frac{H}{\dfrac{\Delta H}{2\Delta S}\ Pair\ 2} = \frac{-R\sin\theta(R^2 - \Delta S^2)}{-(-R^2\cos 2\theta - \Delta S^2)}. \quad (23)$$

[0044]   At this point, there are two unknown parameters (θ and R) with

two equations (Equations (22) and (23)). The ranging distance R and

10   ranging direction θ can thus be determined by solving Equations (22) and

(23) simultaneously, avoiding the use of normal component measurements

at each sensor.

Processing Methods based on Normal Component Measurements

[0045]   In addition to determining the well separation distance, or range

15   R using tangential components, the normal component can be also used

directly to determine the ranging distance and direction.

[0046]   FIG. 7 presents an infinite line source 700 and a downhole tool

housing 710, such as a logging tool, equipped with two sensors S1, S1 for

normal field determination, and indicates H_{y1} and H_{y2} as normal component

20   measurements received at the sensors S1 and S2, respectively. Using the

same definitions provided previously, and Equations (18) and (19), H_{y1} and

H_{y2} can be expressed as:

$$H_{y1} = -H_1\sin(\theta - \alpha_1) - \frac{-I}{2\pi R_1}(\sin\theta\cos\alpha_1 - \cos\theta\sin\alpha_1) - \frac{-I}{2\pi R_1^2}(R\sin\theta)$$

25   , and   (24a)

$$H_{y2} = H_2\sin(\theta + \alpha_2) = \frac{I}{2\pi R_2}(\sin\theta\cos\alpha_2 + \cos\theta\sin\alpha_2) = \frac{I}{2\pi R_2^2}(R\sin\theta)$$

.   (24b)

15

[0047]   In a manner similar to that which was used for Equations (10) and (11), Equations (25) and (26) can be calculated based on the normal component as:

$$H = \frac{H_{y1} - H_{y2}}{2} = \frac{-I}{2\pi R_1^2}(R\sin\theta) - \frac{I}{2\pi R_2^2}(R\sin\theta) = -\frac{2IR\sin\theta}{4\pi R_1^2 R_2^2}(R^2 + \Delta S^2)$$

And   (25)

$$\frac{\Delta H}{2\Delta S} = \frac{H_{y1} + H_{y2}}{2\Delta S} = \frac{-I}{4\Delta S\pi R_1^2}(R\sin\theta) + \frac{I}{4\Delta S\pi R_2^2}(R\sin\theta) = \frac{2IR\sin\theta}{4\pi R_1^2 R_2^2}(2R\cos\theta)$$

.   (26)

[0048]   Taking the ratio of Equation (25) to Equation (26) leads to the formulation of Equation (27) as:

$$\frac{H}{\frac{\Delta H}{2\Delta S}} = -\frac{R^2 + \Delta S^2}{2R\cos\theta} = -\frac{R}{2\cos\theta}(1 + (\frac{\Delta S}{R})^2) .$$ (27)

[0049]   As was accomplished with respect to tangential component calculations, Equation (27) can be used to calculate the ranging distance R based on normal component measurements of H and ΔH, the calculated angle θ, and the known separation distance of ΔS. Again, the tangential and normal components are used to calculate the ranging direction θ in this case. To avoid using this angle in the calculations for tangential component measurements, a second pair of gradient sensors, as shown in Figure 4 of this section, may be utilized to make measurements and obtain and answer from Equation (28), as:

$$\frac{H}{\frac{\Delta H}{2\Delta S}\,Pair2} = \frac{R}{2\sin\theta}(1 + (\frac{\Delta S}{R})^2) .$$ (28)

[0050]   Consequently, the ranging direction θ can be obtained by taking the ratio between Equations (27) and (28), and thereafter the ranging distance R can be calculated from either Equation (27) or Equation (28). In

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addition, the ranging distance R can be also computed without knowing the
ranging direction θ, based on Equation (29), as:

$$\sqrt{\dfrac{1}{\left(\dfrac{\frac{\Delta H}{2\Delta S}}{H}\right)^2_{Pair1}+\left(\dfrac{\frac{\Delta H}{2\Delta S}}{H}\right)^2_{Pair2}}}=$$

$$\sqrt{\dfrac{1}{\dfrac{4\cos^2\theta}{R^2}+\dfrac{4\sin^2\theta}{R^2}}}\left(1+\left(\dfrac{\Delta S}{R}\right)^2\right)=\dfrac{R}{2}\left(1+\left(\dfrac{\Delta S}{R}\right)^2\right) \qquad (29)$$

[0051]   For simplicity, Equation (30) may be used in some

embodiments, since it is common for the value of the ratio $\dfrac{\Delta S}{R}$ to be much

smaller than 1 under field conditions:

$$\sqrt{\dfrac{1}{\left(\dfrac{\frac{\Delta H}{2\Delta S}}{H}\right)^2_{Pair1}+\left(\dfrac{\frac{\Delta H}{2\Delta S}}{H}\right)^2_{Pair2}}}=$$

$$\dfrac{R}{2}\left(1+\left(\dfrac{\Delta S}{R}\right)^2\right)\approx\dfrac{R}{2} \qquad (30)$$

Additional sensor configurations

[0052]   Instead of using two sensors oriented 180 degrees away from
each other, the sensors can be oriented at any tool azimuth location, as long
as the relative azimuth angle between them is known. As shown in FIG. 8,
which presents an infinite line source 800 and a down hole tool housing
810, such as a logging tool, equipped with two sensors S1, S2 for gradient

field determination. Sensor S1 is located at tool azimuth θ_1 and sensor S2 is

located at tool azimuth angle θ_2. The azimuthal difference $\theta_2 - \theta_1$ is known based on the physical sensor locations. This configuration can also utilize all of the methods described above to determine ranging distance and direction.

5   **[0053]**   Another configuration, shown in FIG. 9, which presents an infinite line source 900 and a down hole tool housing 910, such as a logging tool, equipped with three sensors S1, S2, S3 to provide a variety of sets of gradient field measurements. Again, the azimuthal difference between each of the sensors is known (i.e., the difference between the angles

10     $\theta_2 - \theta_1, \theta_3 - \theta_1$, *and* $\theta_3 - \theta_2$ are known).

    [0054]   It is noted that a blind spot sometimes occurs when only two sensors are used in a logging tool. This is because at a certain azimuth angle between the sensors and the line source, the sensors will make nearly identical field measurements, causing gradient field calculations to fail.

15   Therefore, a combination of three or more sensors making measurements at different tool azimuth angles provide gradient measurements that can be used more effectively to determine the ranging distance R – since there will not be any blind spots that appear during some portion of tool housing rotation.

20   **[0055]**   All methods described herein are applicable to any number of sensors that is greater than two, as long as the relative azimuth difference between each sensor is known.

    Another Processing Method for Calculating Distance Using Magnetic Fields

25   **[0056]**   Another set of equations can be used to calculate the distance R to the target well. In this method, the magnetic field gradient shown in prior sections is not used directly. Even so, at least two sensors are used to measure the magnetic fields that are used to calculate the distance R.

    [0057]   Consider two sensors S1, S2 used to measure magnetic fields as

30   shown in FIG. 3. Based on Equation (1), the distance between each sensor and the line source R_1 and R_2 is related to the magnetic field at the position of sensor and the current on source as:

$$\left|H_1\right| = \frac{I}{2\pi R_1} \text{, and} \tag{31a}$$

$$\left|H_2\right| = \frac{I}{2\pi R_2} . \tag{31b}$$

[0058]   Using Equations (31a) and (31b), the ratio of the distance R_1 and R_2 is related to the magnitude of magnetic fields read by the two sensors S1, S2 as:

$$\frac{R_2}{R_1} = \frac{\left|H_1\right|}{\left|H_2\right|} . \tag{32}$$

[0059]   By looking at the geometry of the structure shown in FIG. 3, the relationship between $R_i, i = 1,2$ and the angles can be written as:

$$R_2^2 = R_1^2 + (2\Delta S)^2 - 2R_1(2\Delta S)\cos(\theta - \alpha_1), \tag{33}$$

where $(\theta - \alpha_1)$ can be obtained using the tangential and normal components of the magnetic field measured by sensor S1:

$$(\theta - \alpha_1) = \tan^{-1}\frac{H_{1,tangential}}{H_{1,normal}} . \tag{34}$$

[0060]   Combining Equations (32) and (33) provides Equation (35), where R_1 can be calculated by solving the second-degree equation:

$$R_1^2\left(1-\left(\frac{\left|H_1\right|}{\left|H_2\right|}\right)^2\right) - R_1(4\Delta S\cos(\theta - \alpha_1)) + (2\Delta S)^2 = 0 . \tag{35}$$

[0061]   Once R_1 is obtained, the distance R can be calculated using Equation (36):

$$R^2 = R_1^2 + \Delta S^2 - 2R_1 \Delta S \cos(\theta - \alpha_1). \qquad (36)$$

As discussed previously, to avoid blind spots that may arise during rotation, three sensors can be used to make measurements and computer the range R at all angles of rotation.

[0062]   Thus, consider three sensors attached to a tool housing 910 as shown in FIG. 9. Here, the azimuthal difference between each of the sensors is known (i.e., angles $\theta_2 - \theta_1, \theta_3 - \theta_1,$ and $\theta_3 - \theta_2$ are known). Thus, the distance between each sensor and the source can be written as:

$$\left| H_1 \right| = \frac{I}{2\pi R_1}, \qquad (37a)$$

$$\left| H_2 \right| = \frac{I}{2\pi R_2}, \text{ and} \qquad (37b)$$

$$\left| H_3 \right| = \frac{I}{2\pi R_3}. \qquad (37c)$$

[0063]   By reviewing the geometry of the structure shown in FIG. 9, the relationship between $R_i, i = 1,2,3$, the angles, and the ranging distance R can be calculated as:

$$R^2 = R_1^2 + \Delta S^2 - 2R_1 \Delta S \cos \beta_1, \qquad (38a)$$
$$R^2 = R_2^2 + \Delta S^2 - 2R_2 \Delta S \cos \beta_2, \text{ and} \qquad (38b)$$
$$R^2 = R_3^2 + \Delta S^2 - 2R_3 \Delta S \cos \beta_3, \qquad (38c)$$

where β_i can be acquired using the tangential and normal components of the magnetic field measured by each sensor, as:

$$\beta_i = \tan^{-1}\frac{H_{i,tangential}}{H_{i,normal}}; \quad i = 1,2,3 \quad . \quad (39)$$

Now, using substitution and equations (37), (38), and (39) together, the distance R can be calculated. This method can be applied to any

5   combination or number of sensors.

[0064]   Because the separation distance between sensors is usually small compared to the ranging distance R (e.g., the distance to target well), noise can be a significant source of error. When noise does introduce significant errors into the distance measurement, and there are more than two sensors

10 installed on the tool, the magnitude of the field given by all of the sensors may be examined, and the two sensors providing the largest difference in their magnetic field measurements can be used to calculate the ranging distance R – to help reduce the effect of the noise.

[0065]   These mechanisms permit using a variety of measurements,

15 including the total field, tangential field, or normal field to achieve ranging determination, without knowing or calculating the ranging direction θ between sensors and the target well.

Additional Detailed Description and Some Representative Embodiments

20 [0066]   FIG. 10 is a block diagram of a wireline system 1000 implementation of various embodiments. The system 1000 of FIG. 10 may include any of the embodiments of receiver or sensor mounting discussed previously. In this case, a hoist 1006 may be included as a portion of a platform 1002, such as might be coupled to a derrick 1004, and used to raise

25 or lower equipment such as a wireline sonde 1010 into or out of a borehole. The wireline sonde 1010 may include any one or more of the above-described embodiments, including sensors S1, S2, S3, S4 and a range determination module RD.

[0067]   In this wireline example, a cable 1042 may provide a

30 communicative coupling between a logging facility 1044 (e.g., including a processor circuit 1045 including memory or other storage or control circuitry) and the sonde 1010. In this manner, information about the

formation 1018 may be obtained. The processor circuit 1045 can be configured to access and execute instructions stored in a memory to implement any of the methods described herein (e.g., by accessing a range determination module RD).

5   **[0068]**   FIG. 11 is a block diagram of a drilling system 1100 implementation of various embodiments. This diagram shows a drilling rig system 1100 according to various embodiments that may include MWD or LWD capability. The drilling apparatus can use data from an insert in the drill string 1108, having attached to a number of receivers or sensors as

10   discussed previously, and using acquired and calculated ranging information to steer the drill bit 1114.

      [0069]   A drilling rig or platform 1002 generally includes a derrick 1004 or other supporting structure, such as including or coupled to a hoist 1006. The hoist 1006 may be used for raising or lowering equipment or other

15   apparatus such as drill string 1108. The drill string 1108 may access a borehole 1116, such as through a well head 1012. The lower end of the drill string 1108 may include various apparatus, such as a drill bit 1114, such as to provide the borehole 1116.

      [0070]   A drilling fluid or "mud" may be circulated in the annular

20   region around the drill bit 1114 or elsewhere, such as provided to the borehole 1116 through a supply pipe 1122, circulated by a pump 1120, and returning to the surface to be captured in a retention pit 1124 or sump. Various subs or tool assemblies may be located along the drill string 1108, such as a bottom hole assembly (BHA) 1126 or a second sub 1128. The

25   BHA 1126 and/or the sub 1128 may include one or more sensors S1, S2, S3, S4 or receivers, as described herein, along with a current source (e.g., power supply 148) to initiate a ranging signal, and a processor with access to a memory that contains a program to implement any of the methods described herein (e.g., a ranging determination module RD).

30   **[0071]**   Thus, some of the embodiments described herein may be realized in part, as a set of instructions on a computer readable medium 142 comprising ROM, RAM, CD, DVD, hard drive, flash memory device, or any other computer readable medium, now known or unknown, that when executed causes a computing system, such as computer as illustrated in FIG.

1 or some other form of a data processing device 140, to implement portions
of a method of the present disclosure, for example the processes and
methods described herein (e.g., for computer-assisted well completion).

[0072]   Though sometimes described serially herein, one of ordinary

5   skill in the art would recognize that other examples may reorder the
operations, omit one or more operations, and/or execute two or more
operations in parallel using multiple processors or a single processor
organized as two or more virtual machines or sub-processors. Moreover,
still other examples can implement the operations as one or more specific

10   interconnected hardware or integrated circuit modules with related control
and data signals communicated between and through the modules. Thus,
any process flow is applicable to software, firmware, hardware, and hybrid
implementations.

[0073]   It is expected that the system range and performance can be

15   extended with the various embodiments described herein. Power can often
be saved, and accuracy of ranging measurements improved. Signal
components may be extracted and converted to pixel colors or intensities
and displayed as a function of tool position and azimuth. Assuming the
target casing string is within detection range, it may appear as a bright (or, if

20   preferred, a dark) band in the image. The color or brightness of the band
may indicate the distance to the casing string, and the position of the band
indicates the direction to the casing string. Thus, by viewing such an image,
a driller can determine in a very intuitive manner whether the new borehole
is drifting from the desired course and he or she can quickly initiate

25   corrective action. For example, if the band becomes dimmer, the driller can
steer towards the casing string. Conversely, if the band increases in
brightness, the driller can steer away from the casing string. If the band
deviates from its desired position directly above or below the casing string,
the driller can steer laterally to re-establish the desired directional

30   relationship between the boreholes.

[0074]   While the text of this document has been divided into sections, it
should be understood that this has been done as a matter of convenience,
and that the embodiments discussed in any one section may form a part of
any or more embodiments described in another section, and vice-versa.

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Moreover, various embodiments described herein may be combined with each other, without limitation. Thus, many embodiments may be realized.

[0075]   Similarly, while some of the above-described embodiments may show only one receiver, perhaps in the form of a magnetometer, coil, or

5   telemetry receiver, one of ordinary skill in the art would realize that a drill string or downhole tool may include multiple receivers for making the various measurements described herein. Examples of various embodiments will now be listed in a non-limiting fashion.

[0076]   In some embodiments, an apparatus comprises   a down hole tool

10   housing attached to two sensors rotatable by a selected number of degrees in an azimuthal plane, each of the sensors to measure an electromagnetic field strength component comprising at least a normal component, a tangential component, or a total field component. In some embodiments, the selected number of degrees of rotation are selected to provide a threshold gradient field magnitude. In some

15   embodiments, the selected number of degrees of rotation are selected to provide a threshold gradient field magnitude above a determined noise level.

[0077]   In some embodiments, the apparatus further comprises a range determination module to receive the normal component, the tangential component, or the total field component as a first set of field strength

20   components from each of the two sensors provided by the two sensors when the two sensors are located at a first azimuthal location, and as a second set of field strength components from each of the two sensors provided by the two sensors when the two sensors are located at a second azimuthal location different from the first location. In some embodiments, the range determination module is to

25   determine an approximate range from the two sensors disposed in a second well, to a first well, via direct transmission or backscatter transmission of an electromagnetic field from the first well, when a range direction associated with the housing upon which the two sensors are mounted is unknown.

[0078]   In some embodiments of the apparatus, or a system, or a method, a

30   vector sum of the normal component and the tangential component and/or the longitudinal component provides the total field component. In some embodiments, the range determination module is to determine the approximate range as a combination of the range direction and a range distance from the

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second well to the first well based on the normal component, the tangential component, or the total field component.

[0079]   In some embodiments, an apparatus comprises a down hole tool housing attached to two sensors, each of the sensors to measure a set of

5   electromagnetic field strength components comprising a normal component, a tangential component, and a longitudinal component. In some embodiments, the apparatus comprises a range determination module to receive the set of electromagnetic field strength components from each of the two sensors, and to determine an approximate range from the two sensors disposed in a second well,

10   to a first well, via direct transmission or backscatter transmission of an electromagnetic field from the first well, when a range direction associated with the housing upon which the two sensors are mounted is unknown.

[0080]   In some embodiments, the set of electromagnetic field strength components comprises a first group of measurements made at a first elevation in

15   the second well, and the set of electromagnetic field strength components comprises a second group of measurements made at a second elevation in the second well.

[0081]   In some embodiments, the set of electromagnetic field strength components comprises a first group of measurements made at a first azimuthal

20   location in the second well, and the set of electromagnetic field strength components comprises a second group of measurements made at a second azimuthal location in the second well.

[0082]   In some embodiments, a system comprises a current source (e.g., a power supply) to couple current to one of a target well or a drilling well. In some

25   embodiments, the system may comprise an apparatus that includes a range determination module to receive a normal component, a tangential component, or a total field component of an electromagnetic field strength measurement of a magnetic field created by flow of the current in the target well or the drilling well, as a first set of field strength components from each of at least two sensors

30   provided by the sensors when the sensors are located at a first azimuthal location within the drilling well, and as a second set of field strength components from each of the sensors provided by the sensors when the sensors are located at a second azimuthal location within the drilling well. In some embodiments, the range determination module is to determine an approximate range from the

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sensors disposed in the drilling well to the target well, via direct transmission
from the target well, or via backscatter transmission from the target well, when a
range direction associated with a housing upon which the sensors are mounted is
unknown.

5   **[0083]**   In some embodiments, the first and the second sets comprise the
normal components or total field components, and the range determination
module is to determine a range distance R from the equation

$$\sqrt{\dfrac{1}{\left(\dfrac{\dfrac{\Delta H}{2\Delta S}}{H}\right)^2_{First\ Set} + \left(\dfrac{\dfrac{\Delta H}{2\Delta S}}{H}\right)^2_{Second\ Set}}},$$

10   wherein ΔH is a field difference between field strength components of the first or
the second sets, H is a field sum between field strength components of the first
or the second sets , and wherein $2\Delta S$ is separation distance between the at least
two sensors. This equation is applicable for both normal component calculation
or total field component calculation. The only difference is the corresponding
15   relationship of the equation to the ranging distance and the ranging direction, as
indicated in the following paragraphs.

[0084]   In some embodiments, the first and the second sets comprise the
normal component, and the range determination module is to calculate a portion
of a first equation based on the first set of field strength components as

20

$$\dfrac{H}{\dfrac{\Delta H}{2\Delta S}}_{First\ Set} = -\dfrac{R}{2\cos\theta}\left(1 + \left(\dfrac{\Delta S}{R}\right)^2\right),$$

wherein the approximate range comprises R as a range distance and Θ as a range
direction, and wherein $2\Delta S$ is separation distance between the at least two
25   sensors; and wherein the range determination module is to calculate a portion of
a second equation based on the second set of field strength components as

$$\frac{\dfrac{H}{\Delta H}}{2\Delta S}_{Second\ Set} = \frac{R}{2\sin\theta}(1+(\frac{\Delta S}{R})^2)$$, such that a ratio of the first

equation and the second equation provides the range direction . In some

embodiments, the range distance is determined by either the first or the second

equation without knowing the range direction Θ.

[0085]   In some embodiments, the first and the second sets comprise the

tangential component, and the range determination module is to calculate a

portion of a first equation based on the first set of field strength components as

$$\frac{\dfrac{H}{\Delta H}}{2\Delta S}_{First\ Set} = -\frac{R\cos\theta(R^2-\Delta S^2)}{(R^2\cos 2\theta - \Delta S^2)}$$

wherein the approximate range comprises R as a range distance and Θ as a range

direction, and wherein $2\Delta S$ is separation distance between the at least two

sensors; and wherein the range determination module is to calculate a portion of

a second equation based on the second set of field strength components as

$$\frac{\dfrac{H}{\Delta H}}{2\Delta S}_{Second\ Set} = \frac{R\sin\theta(R^2-\Delta S^2)}{(-R^2\cos 2\theta - \Delta S^2)}$$, to provide both the range

distance and the range direction.

[0086]   In some embodiments, the first and the second sets comprise the total

field component, and the range determination module is to calculate a portion of

a first equation based on the first set of field strength components as

$$\frac{\dfrac{H}{\Delta H}}{2\Delta S}_{First\ Set} \approx -\frac{R}{\cos\theta}$$

wherein the approximate range comprises R as a range distance and Θ as a range direction, and wherein $2\Delta S$ is separation distance between the at least two sensors; and wherein the range determination module is to calculate a portion of a second equation based on the second set of field strength components as

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$$\frac{H}{\dfrac{\Delta H}{2\Delta S}}_{\text{Second Set}} \approx \frac{R}{\sin\theta}$$, such that a ratio of the first equation and the second

equation provides the range direction . In some embodiments, the range distance can be determined by either the first or the second equation without knowing the range direction Θ.

[0087]   In some embodiments, a system comprises a current source (e.g., a

10   power supply) to couple current to one of a target well or a drilling well. In some embodiments, the system comprises an apparatus that includes a down hole tool housing attached to two sensors, each of the two sensors to measure a set of electromagnetic field strength components comprising a normal component, a tangential component, or a longitudinal component. In some embodiments, the

15   system further comprises a range determination module to receive the set of electromagnetic field strength components from each of the two sensors, values of the set determined by a field strength due to flow of the current in the target well or the drilling well. In some embodiments, the range determination module is to determine an approximate range from the two sensors disposed in the

20   drilling well, to the target well, via direct transmission or backscatter transmission of an electromagnetic field characterized by the field strength, when a range direction associated with the housing upon which the two sensors are mounted is unknown.

[0088]   In some embodiments, the range determination module is to use a

25   combination of ratios of the electromagnetic field strength components and a separation distance between the two sensors to determine the approximate range as a combination of a range distance and a range direction.

[0089]   In some embodiments, the down hole tool housing is attached to a third sensor, and the range determination module is to use a subset of the

30   electromagnetic field strength components that have a greatest difference in measured component values to determine the approximate range.

[0090]　　In some embodiments, a method comprises receiving normal, tangential, and longitudinal components of electromagnetic field strength measurements within a first well as a set of field strength components from at least one sensor, wherein the at least one sensor is used to take multiple

5　azimuthal field strength measurements at a single depth. In some embodiments, the method further comprises determining an approximate range from the at least one sensor to a second well that serves as a source of an electromagnetic field, via direct transmission or backscatter transmission, when a range direction associated with a housing upon which the at least one sensor is mounted is

10　unknown.

[0091]　　In some embodiments, the method comprises receiving the normal, tangential, or total field components as a first set of field strength components from each of two sensors when the two sensors are located at a first azimuthal location within the first well; receiving the normal, tangential, or total field

15　components as a second set of field strength components from each of the two sensors when the two sensors are located at a second azimuthal location within the first well different from the first location; and determining the approximate range from the two sensors disposed within the first well, to the second well, using only one of the normal, the tangential or the total field components,

20　respectively.

[0092]　　In some embodiments, the method comprises comparing signal magnitudes in the electromagnetic field strength measurements; determining a subset of the electromagnetic strength field strength measurements that have a greatest difference in measured component values; and selecting the subset to

25　determine the approximate range.

[0093]　　In some embodiments, a method comprises receiving normal, tangential, or total field components of electromagnetic field strength measurements within a first well as a set of field strength components from each of at least three sensors located at three different azimuthal locations while the

30　sensors remain relatively stationary within the first well. In some embodiments, the method comprises determining an approximate range from the sensors to a second well that serves as a source of an electromagnetic field, via direct transmission or backscatter transmission, when a range direction associated with a housing upon which the sensors are mounted is unknown.

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[0094] In some embodiments, an apparatus comprises a down hole tool housing (e.g., ranging tool 124) attached to a set of sensors, the down hole tool housing comprising one or more of a wireline sonde, a bottom hole assembly, a drill collar, a drill string pipe, or a sub. Some embodiments of this apparatus further comprise a processor (e.g., computer 140) communicatively coupled to the set of sensors to receive electromagnetic signal strength signals from the sensors, and to a memory (e.g., medium 142), the memory having a set of instructions which, when executed by the processor, cause the processor to implement any of the methods described herein.

[0095] In some embodiments, a system comprises a source of current or voltage (e.g., power supply 148) to electrically couple to a well casing of a first well or to attach to a first down hole tool housing. Some embodiments of this system further comprise a drill string to be disposed in a second well and mechanically coupled to a second down hole tool housing, the second down hole tool housing attached to a set of sensors. Some embodiments of this system further comprise a processor (e.g., computer 140) communicatively coupled to the set of sensors to receive signals representing electromagnetic field strength from the sensors, in response to the source exciting the well casing directly to initiate direct signal transmission, or indirectly via backscatter transmission, the processor communicatively coupled to a memory (e.g., medium 142) having a set of instructions which, when executed by the processor, cause the processor to implement any of the methods described herein.

[0096] Numerous other variations and modifications will become apparent to those skilled in the art once the above disclosure is fully appreciated. For example, the foregoing discussion has focused on a logging while drilling implementation, but the disclosed techniques would also be suitable for wireline tool implementation (as shown in FIG. 10).

[0097] In this description, references to "one embodiment" or "an embodiment," or to "one example" or "an example" mean that the feature being referred to is, or may be, included in at least one embodiment or example of the invention. Separate references to "an embodiment" or "one embodiment" or to "one example" or "an example" in this description are

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not intended to necessarily refer to the same embodiment or example; however, neither are such embodiments mutually exclusive, unless so stated or as will be readily apparent to those of ordinary skill in the art having the benefit of the knowledge provided by this disclosure. Thus, the present

5   disclosure includes a variety of combinations and/or integrations of the embodiments and examples described herein, as well as further embodiments and examples.

[0098]   The accompanying drawings that form a part hereof, show by way of illustration, and not of limitation, specific embodiments in which the

10   subject matter may be practiced. The embodiments illustrated are described in sufficient detail to enable those skilled in the art to practice the teachings disclosed herein. Other embodiments may be used and derived therefrom, such that structural and logical substitutions and changes may be made without departing from the scope of this disclosure. This Detailed

15   Description, therefore, is not to be taken in a limiting sense.

<u>CLAIMS</u>

What is claimed is:

5   1.   An apparatus, comprising:

a down hole tool housing attached to two sensors rotatable by a selected number of degrees in an azimuthal plane, each of the sensors to measure an electromagnetic field strength component comprising at least a normal component, a tangential component, or a total field component; and

10   a range determination module to:

receive the normal component, the tangential component, or the total field component as a first set of field strength components from each of the two sensors provided by the two sensors when the two sensors are located at a first azimuthal location, and as a second set of field strength components from each of

15   the two sensors provided by the two sensors when the two sensors are located at a second azimuthal location different from the first location, and

determine an approximate range from the two sensors disposed in a second well, to a first well, as a combination of the range direction and a range distance from the second well to the first well based on the normal component,

20   the tangential component, or the total field component of the two sensors at the first and the second azimuthal location, via direct transmission or backscatter transmission of an electromagnetic field from the first well, when a range direction associated with the housing upon which the two sensors are mounted is unknown.

25   2.   The apparatus of claim 1, wherein a vector sum of the normal component and the tangential component and/or the longitudinal component provides the total field component.

3.   The apparatus of claim 1, wherein the selected number of degrees of rotation are selected to provide a threshold gradient field magnitude.

30   4.   The apparatus of claim 3, wherein the selected number of degrees of rotation are selected to provide a threshold gradient field magnitude above a determined noise level.

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5.   An apparatus, comprising:

a down hole tool housing attached to two sensors, each of the sensors to measure a set of electromagnetic field strength components comprising a normal component, a tangential component, and a longitudinal component; and

a range determination module to receive the set of electromagnetic field strength components from each of the two sensors, and to determine an approximate range from the two sensors disposed in a second well, to a first well, via direct transmission or backscatter transmission of an electromagnetic field from the first well, when a range direction associated with the housing upon which the two sensors are mounted is unknown, using a combination of ratios of the electromagnetic field strength components and a separation distance between the two sensors at two different azimuthal locations, to determine the approximate range as a combination of a range distance and a range direction.

6.   The apparatus of claim 5, wherein the set of electromagnetic field strength components comprises a first group of measurements made at a first elevation in the second well, and wherein the set of electromagnetic field strength components comprises a second group of measurements made at a second elevation in the second well.

7.   The apparatus of claim 5, wherein the set of electromagnetic field strength components comprises a first group of measurements made at a first azimuthal location in the second well, and wherein the set of electromagnetic field strength components comprises a second group of measurements made at a second azimuthal location in the second well.

8.   A system, comprising:

a current source to couple current to one of a target well or a drilling well; and

an apparatus comprising a range determination module to receive a normal component, a tangential component, or a total field component of an electromagnetic field strength measurement of a magnetic field created by flow of the current in the target well or the drilling well, as a first set of field strength components from each of at least two sensors provided by the sensors when the sensors are located at a first azimuthal location within the drilling well, and as a second set of field strength components from each of the sensors provided by the sensors when the sensors are

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located at a second azimuthal location within the drilling well, and to determine an approximate range from the sensors disposed in the drilling well to the target well, as a combination of the range direction and a range distance from the second well to the first well based on the normal component, the tangential component, or the total field component at the first and at the second azimuthal location, via direct transmission from the target well, or via backscatter transmission from the target well, when a range direction associated with a housing upon which the sensors are mounted is unknown.

9.   The system of claim 8, wherein the first and the second sets comprise the normal components or the total field components, and the range determination module is to determine a range distance R from the equation

$$\sqrt{\dfrac{1}{\left(\dfrac{\frac{\Delta H}{2\Delta S}}{H}\right)^2_{First\,Set} + \left(\dfrac{\frac{\Delta H}{2\Delta S}}{H}\right)^2_{Second\,Set}}},$$

wherein ΔH is a field difference between field strength components of the first or the second sets, H is a field sum between field strength components of the first or the second sets , and wherein $2\Delta S$ is separation distance between the at least two sensors.

10.   The system of claim 8, wherein the first and the second sets comprise the normal component, and the range determination module is to calculate a portion of a first equation based on the first set of field strength components as

$$\dfrac{\dfrac{H}{\Delta H}}{2\Delta S}_{First\,Set} = -\dfrac{R}{2\cos\theta}\left(1 + \left(\dfrac{\Delta S}{R}\right)^2\right)$$, wherein the approximate

range comprises R as a range distance and Θ as a range direction, and wherein $2\Delta S$ is separation distance between the at least two sensors; and wherein the range determination module is to calculate a portion of a second equation based on the second

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set of field strength components as $\dfrac{\dfrac{H}{\Delta H}}{2\Delta S}_{Second\,Set} = \dfrac{R}{2\sin\theta}(1+(\dfrac{\Delta S}{R})^2)$, such

that a ratio of the first equation and the second equation provides the range direction.

11. The system of claim 8, wherein the first and the second sets comprise the tangential component, and the range determination module is to calculate a portion of a

5   first equation based on the first set of field strength components as

$$\dfrac{\dfrac{H}{\Delta H}}{2\Delta S}_{First\,Set} = -\dfrac{R\cos\theta(R^2 - \Delta S^2)}{(R^2\cos 2\theta - \Delta S^2)}$$, wherein the approximate

range comprises R as a range distance and Θ as a range direction, and wherein $2\Delta S$ is separation distance between the at least two sensors; and wherein the range determination module is to calculate a portion of a second equation based on the second

10   set of field strength components as $\dfrac{\dfrac{H}{\Delta H}}{2\Delta S}_{Second\,Set} = \dfrac{R\sin\theta(R^2 - \Delta S^2)}{(-R^2\cos 2\theta - \Delta S^2)}$, to

provide both the range distance and the range direction.

12. The system of claim 8, wherein the first and the second sets comprise the total field component, and the range determination module is to calculate a portion of a first equation based on the first set of field strength components as

15    $$\dfrac{\dfrac{H}{\Delta H}}{2\Delta S}_{First\,Set} \approx -\dfrac{R}{\cos\theta}$$, wherein the approximate range comprises R as a

range distance and Θ as a range direction, and wherein $2\Delta S$ is separation distance between the at least two sensors; and wherein the range determination module is to calculate a portion of a second equation based on the second set of field strength

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components as $\dfrac{\dfrac{H}{\Delta H}}{2 \Delta S}_{Second Set} \approx \dfrac{R}{\sin \theta}$, such that a ratio of the first equation and the

second equation provides the range direction.

13.   A system, comprising:

a current source to couple current to one of a target well or a drilling well; and

an apparatus comprising a down hole tool housing attached to two sensors, each of the two sensors to measure a set of electromagnetic field strength components comprising a normal component, a tangential component, or a longitudinal component, and a range determination module to receive the set of electromagnetic field strength components from each of the two sensors, values of the set determined by a field strength due to flow of the current in the target well or the drilling well, and to determine an approximate range from the two sensors disposed in the drilling well, to the target well, via direct transmission or backscatter transmission of an electromagnetic field characterized by the field strength, when a range direction associated with the housing upon which the two sensors are mounted is unknown, using a combination of ratios of the electromagnetic field strength components and a separation distance between the two sensors at two different azimuthal locations to determine the approximate range as a combination of a range distance and a range direction.

14.   The system of claim 13, wherein the down hole tool housing is attached to a third sensor, and wherein the range determination module is to use a subset of the electromagnetic field strength components that have a greatest difference in measured component values to determine the approximate range.

15.   A method, comprising:

receiving normal, tangential, and longitudinal components of electromagnetic field strength measurements within a first well as a set of field strength components from at least one sensor, wherein the at least one sensor is used to take multiple azimuthal field strength measurements at a single depth; and

determining an approximate range from the at least one sensor to a second well that serves as a source of an electromagnetic field, via direct transmission or backscatter transmission, when a range direction associated with a housing upon which the at least

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one sensor is mounted is unknown, using a combination of ratios of the electromagnetic field strength components and the distance between two different azimuthal locations to determine the approximate range as a combination of a range distance and a range direction.

5   16.   The method of claim 15, further comprising:

receiving the normal, tangential, or total field components as a first set of field strength components from each of two sensors when the two sensors are located at a first azimuthal location within the first well;

receiving the normal, tangential, or total field components as a second set of field
10   strength components from each of the two sensors when the two sensors are located at a second azimuthal location within the first well different from the first location; and

determining the approximate range from the two sensors disposed within the first well, to the second well, using only one of the normal, the tangential or the total field components, respectively.

15   17.   The method of claim 16, further comprising:

comparing signal magnitudes in the electromagnetic field strength measurements;

determining a subset of the electromagnetic strength field strength measurements that have a greatest difference in measured component values; and

selecting the subset to determine the approximate range.

20   18.   A method, comprising:

receiving normal, tangential, or total field components of electromagnetic field strength measurements within a first well as a set of field strength components from each of at least three sensors located at three different azimuthal locations while the sensors remain relatively stationary within the first well; and

25   determining an approximate range from the sensors to a second well that serves as a source of an electromagnetic field as a combination of the range direction and a range distance from the second well to the first well based on the normal component, the tangential component, or the total field component at the three different azimuthal locations, via direct transmission or backscatter transmission, when a range direction
30   associated with a housing upon which the sensors are mounted is unknown.

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19.   The apparatus of claim 1, wherein each of the two sensors are attached on the down hole tool housing at a different azimuthal location.

20.   The apparatus of claim 5, wherein each of the two sensors are attached on the down hole tool housing at a different azimuthal location.

5   21.   The system of claim 8, wherein each of the at least two sensors are attached on a down hole tool housing at a different azimuthal location.

22.   The system of claim 13, wherein each of the two sensors are attached on the down hole tool housing at a different azimuthal location.

23.   The method of claim 15, wherein the at least one sensor comprises two sensors
10   and wherein each of the two sensors are attached on a down hole tool housing at a different azimuthal location.
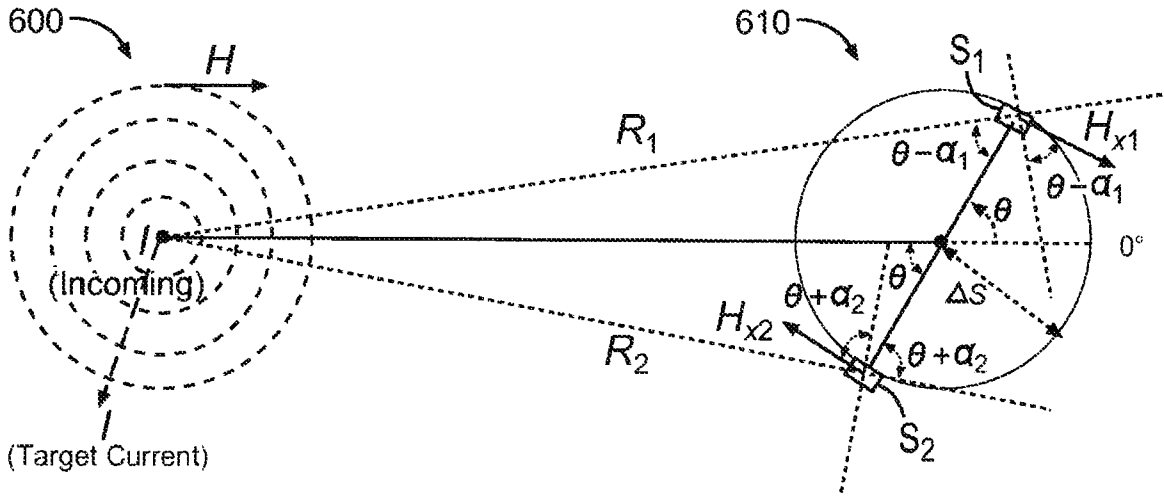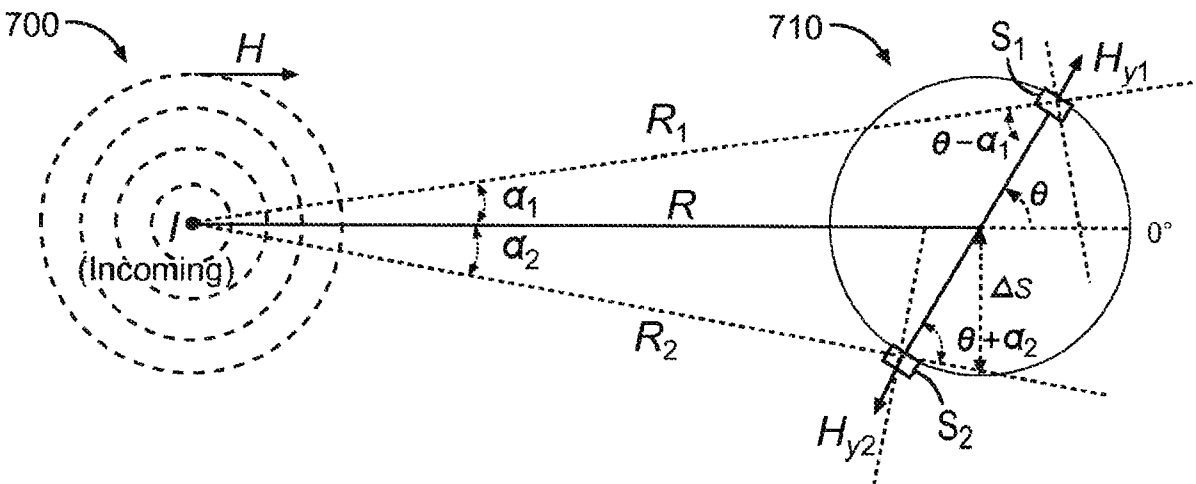
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Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

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Fig. 8

Fig. 9

Fig. 10

Fig. 11

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