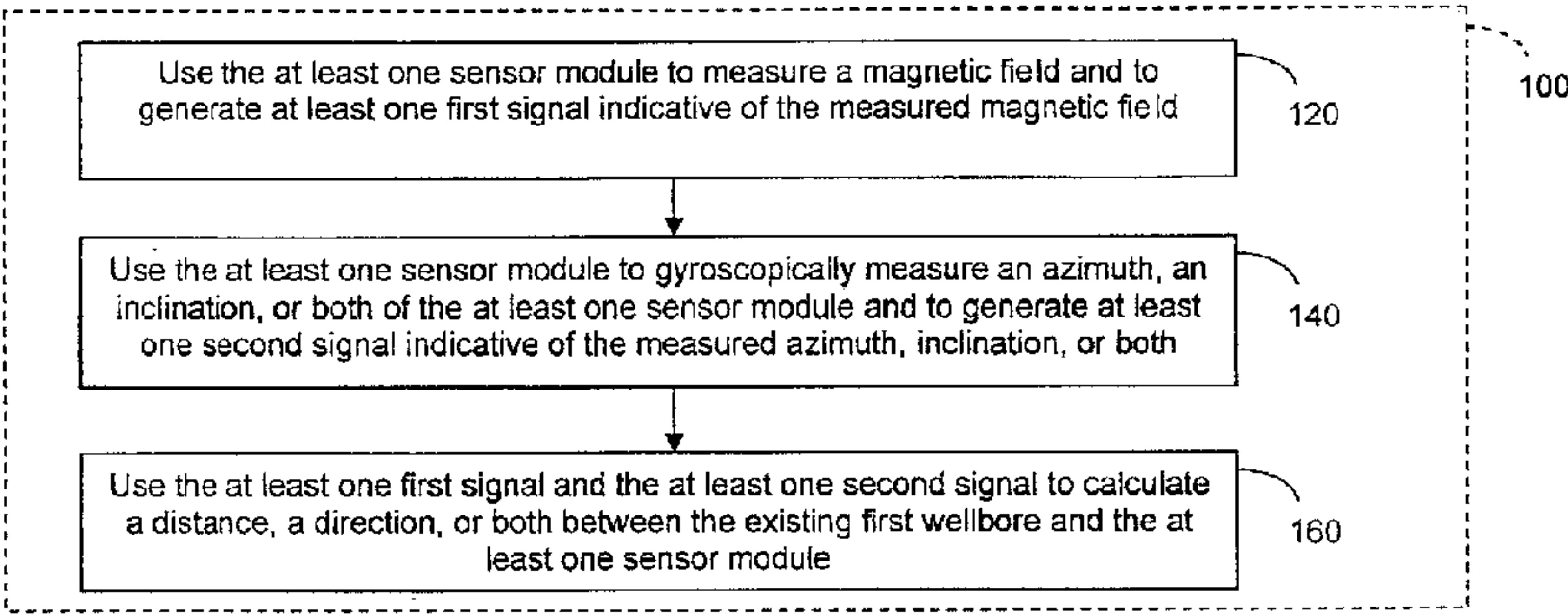




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(54) **Titre :** TECHNIQUES DE POSITIONNEMENT DANS LES ENVIRONNEMENTS MULTIPUITS
(54) **Title:** POSITIONING TECHNIQUES IN MULTI-WELL ENVIRONMENTS



(57) **Abrégé/Abstract:**

A method is provided to determine a distance, a direction, or both between an existing first wellbore and at least one sensor module of a drill string within a second wellbore being drilled. The method includes using the at least one sensor module to measure a magnetic field and to generate at least one first signal indicative of the measured magnetic field. The method further includes using the at least one sensor module to gyroscopically measure an azimuth, an inclination, or both of the at least one sensor module and to generate at least one second signal indicative of the measured azimuth, inclination, or both. The method further includes using the at least one first signal and the at least one second signal to calculate a distance between the existing first wellbore and the at least one sensor module, a direction between the existing first wellbore and the at least one sensor module, or both a distance and a direction between the existing first wellbore and the at least one sensor module.

ABSTRACT

A method is provided to determine a distance, a direction, or both between an existing first wellbore and at least one sensor module of a drill string within a second wellbore being drilled. The method includes using the at least one sensor module to measure a magnetic field and to generate at least one first signal indicative of the measured magnetic field. The method further includes using the at least one sensor module to gyroscopically measure an azimuth, an inclination, or both of the at least one sensor module and to generate at least one second signal indicative of the measured azimuth, inclination, or both. The method further includes using the at least one first signal and the at least one second signal to calculate a distance between the existing first wellbore and the at least one sensor module, a direction between the existing first wellbore and the at least one sensor module, or both a distance and a direction between the existing first wellbore and the at least one sensor module.

POSITIONING TECHNIQUES IN MULTI-WELL ENVIRONMENTS

[0001]

BACKGROUND

Field

[0002] This application relates generally to wellbore drilling and, more particularly, to systems and methods for determining the relative and absolute spatial positions of multiple subterranean wellbores for drilling the wellbores in close proximity to each other for a substantial part of their length, for the avoidance of collisions between wellbores, or for interceptions of the wellbores at all angles.

Description of the Related Art

[0003] To determine the most accurate, absolute spatial position of a wellbore, accurate survey instruments are desirable. Instrument or measurement errors can result in errors in the spatial position (e.g., an angular error of ± 0.3 degree can result in a positional error of ± 5.24 meters over a 1000 meter length). In a two-well scenario when both wells have a similar sized angular error, it is possible for their relative displacement error to be as large as 10.48 meters over a 1000 meter length.

[0004] Conventional techniques for drilling a second wellbore in proximity to a first wellbore (e.g., sidetracking) utilize a magnetic sensor (e.g., a measurement while drilling or MWD system) within the second wellbore to detect a magnetic field emanating from the first wellbore (e.g., from a magnetic field source such as an electromagnet, run in AC or DC mode, magnetized casing or a “fish” within the first wellbore). Information generated by the MWD system is transmitted to the surface (e.g., via mud pulse telemetry) where an operator can use the information to control the direction (e.g., steer) the drilling tool. However, uncertainties associated with such conventional magnetic-based surveying techniques can generate time-consuming challenges when drilling the second wellbore in proximity to the first wellbore, particularly at high inclinations. For example, if the target trajectory of the second wellbore (e.g., the sidetrack wellbore) is not planned with a significant safety margin and/or the bottom-hole assembly (BHA) within the second wellbore does not include the

proper amount of non-magnetic spacing, then the MWD surveys of the second wellbore can be compromised significantly by external magnetic interference from the BHA, formation, magnetic mud, magnetic storms, target well magnetism, leaving the second wellbore to effectively be drilled blind. One possibility for monitoring the approach between a first wellbore and a second wellbore can be to use the MWD sensors to monitor external magnetic interference, and in close approach situations to calculate the relative positions between the sidetrack wellbore and the fish in the first wellbore. However, calculating the relative position between wellbores can be challenging when the inclination between the two wellbores exceeds about 80 degrees.

SUMMARY

[0005] In certain embodiments, a method is provided to determine a distance, a direction, or both between an existing first wellbore and at least one sensor module of a drill string within a second wellbore being drilled. The method comprises using the at least one sensor module to measure a magnetic field and to generate at least one first signal indicative of the measured magnetic field. The method further comprises using the at least one sensor module to gyroscopically measure an azimuth, an inclination, or both of the at least one sensor module and to generate at least one second signal indicative of the measured azimuth, inclination, or both. The method further comprises using the at least one first signal and the at least one second signal to calculate a distance between the existing first wellbore and the at least one sensor module, a direction between the existing first wellbore and the at least one sensor module, or both a distance and a direction between the existing first wellbore and the at least one sensor module.

[0006] In certain embodiments, a method is provided for controlling a drill string spaced from an existing first wellbore, the drill string drilling a second wellbore. The method comprises receiving at least one first signal indicative of a magnetic field measured by at least a first sensor module of the drill string. The method further comprises receiving at least one second signal indicative of an azimuth, an inclination, or both measured by at least a second sensor module of the drill string. The second sensor module comprises at least one gyroscopic sensor. The method further comprises calculating a distance between the existing first wellbore and the first sensor module, a direction between the existing first wellbore and the first sensor module, or both a distance and a direction between the existing first wellbore

and the first sensor module. The method further comprises generating, in response to at least one of the calculated distance and the calculated direction, at least one control signal to be transmitted to a steering mechanism of the drill string.

[0007] In certain embodiments, a method is provided for using a drilling tool to drill a second wellbore along a desired path substantially parallel to a first wellbore. The drilling tool comprises a steering mechanism. The method comprises defining a first target position along a desired path of the second wellbore. The first target position is spaced from a current position of the drilling tool by a first distance. The method further comprises performing magnetic ranging measurements and gyroscopic measurements of an azimuth, an inclination, or both of the drilling tool and using the magnetic ranging measurements and the gyroscopic measurements to determine a second distance between the current position of the drilling tool and the first wellbore. The method further comprises calculating a third distance between the first wellbore and the desired path of the second wellbore. The method further comprises calculating a target sightline angle with respect to the desired path of the second wellbore. The method further comprises measuring a tool path direction with respect to the first wellbore. The method further comprises calculating a steering angle. The method further comprises transmitting a steering signal to the steering mechanism to control the steering mechanism to adjust a tool path direction of the second wellbore by the steering angle. The method further comprises actuating the steering mechanism to move the drilling tool to a revised current position.

[0008] In certain embodiments, a method is provided for gyro-assisted magnetic ranging relative to a first wellbore using a rotary steerable drilling tool to drill a second wellbore. The method comprises steering the drilling tool to a position at which a magnetic field from an electromagnet in the first wellbore can be detected by at least one sensor module of the drilling tool. The method further comprises performing a multi-station analysis to detect magnetic biases from the drilling tool. The method further comprises monitoring measurements from a longitudinal axis magnetometer of the at least one sensor module as a drill path of the second wellbore approaches the electromagnet in the first wellbore. The method further comprises making stationary magnetic ranging survey measurements using the at least one sensor module. The method further comprises moving the electromagnet to a different position within the first wellbore. The method further

comprises making magnetic ranging measurements and further drilling the second wellbore in a trajectory that is substantially parallel to the first wellbore. The method further comprises making stationary gyro survey measurements using the at least one sensor module and using the stationary gyro survey measurements to determine a separation and angle of approach of the at least one sensor module to the first wellbore. The method further comprises using the stationary gyro survey measurements to compute drilling commands to be performed by the drilling tool and continuing to drill the second wellbore.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] Various configurations are depicted in the accompanying drawings for illustrative purposes, and should in no way be interpreted as limiting the scope of the systems or methods described herein. In addition, various features of different disclosed configurations can be combined with one another to form additional configurations, which are part of this disclosure. Any feature or structure can be removed, altered, or omitted. Throughout the drawings, reference numbers may be reused to indicate correspondence between reference elements.

[0010] Figure 1 schematically illustrates an example target box in a cross-sectional view in a plane generally perpendicular to a first wellbore (e.g., a target well) and to a second wellbore (e.g., a drilling well) generally parallel to the first wellbore in accordance with certain embodiments described herein.

[0011] Figure 2A schematically illustrates an example electromagnet with its magnetic field shown by magnetic flux lines in accordance with certain embodiments described herein.

[0012] Figures 2B schematically illustrates an example extended range magnetic tool (XMT) comprising an electromagnet compatible with certain embodiments described herein.

[0013] Figure 3A schematically illustrates an example cross-sectional view of the cross-axial magnetic flux pattern in a plane generally perpendicular to the first wellbore (e.g., target well) and to the second wellbore (e.g., drilling well) in accordance with certain embodiments described herein.

[0014] Figure 3B shows a magnetic map of the magnetic field magnitude (in gauss) of the XMT of Figure 2B in a horizontal plane perpendicular to a longitudinal axis of the XMT.

[0015] Figure 4 is a schematic diagram of the magnetic field of an example electromagnetic target between two casing joints of a target well in accordance with certain embodiments described herein.

[0016] Figure 5A is a flow diagram of an example method to determine a distance, a direction, or both between an existing first wellbore and at least one sensor module of a drill string within a second wellbore being drilled in accordance with certain embodiments described herein.

[0017] Figure 5B is a flow diagram of an example method for controlling a drill string spaced from an existing first wellbore, the drill string drilling a second wellbore, in accordance with certain embodiments described herein.

[0018] Figures 6A schematically illustrates the positions of a number of standard magnetic ranging survey measurements to be taken along a target box 570 meters long.

[0019] Figure 6B schematically illustrates the positions of a fewer number of gyro-assisted ranging survey measurements to be taken along the target box of Figure 6A in accordance with certain embodiments described herein.

[0020] Figure 7 schematically illustrates a comparison between balanced electromagnetic vectors and unbalanced electromagnetic vectors due to BHA interference.

[0021] Figure 8A schematically illustrates an example configuration of a drilling tool configured to drill a second wellbore (e.g., drilling well) along a desired path parallel to and in close proximity to a first wellbore (e.g., target well) in accordance with certain embodiments described herein.

[0022] Figure 8B is a flow diagram of an example method of drilling a second wellbore (e.g., drilling well) along a desired path parallel to and in close proximity to a first wellbore (e.g., target well) in accordance with certain embodiments described herein.

[0023] Figure 9 schematically illustrates an example measurement of the tool path direction (α) with respect to the first wellbore path using the first sensor module and the second sensor module in accordance with certain embodiments described herein.

[0024] Figure 10 schematically illustrates an example progression of the drill string using multiple iterations of the example method of Figure 8B in accordance with certain embodiments described herein.

[0025] Figure 11 schematically illustrates the first and second wellbores in a plan view from above the Earth's surface in a direction perpendicular to the Earth's surface and in a section view in a direction parallel to the Earth's surface.

[0026] Figure 12A schematically illustrates the magnetic field generated by an electromagnet in accordance with certain embodiments described herein.

[0027] Figure 12B schematically illustrates an SAGD configuration in which a portion of the first wellbore is in proximity to and parallel to a portion of the second wellbore.

[0028] Figure 12C schematically illustrates a horizontal to vertical interception configuration in which the switch pattern occurs at the point of closest approach of the first wellbore to the second wellbore.

[0029] Figure 13A schematically illustrates an example configuration including a table of example measured values of the various parameters of the magnetic field from the electromagnet in accordance with certain embodiments described herein.

[0030] Figure 13B schematically illustrates an example well paralleling configuration including a table of example measured values of the various parameters of the magnetic field from the electromagnet 60 in accordance with certain embodiments described herein.

[0031] Figure 13C schematically illustrates an example horizontal to vertical interception configuration including a table of example measured values of the various parameters of the magnetic field from the electromagnet in accordance with certain embodiments described herein.

[0032] Figure 14 is a flow diagram of an example method for gyro-assisted magnetic ranging in the context of SAGD drilling using a rotary steerable drilling tool in accordance with certain embodiments described herein.

DETAILED DESCRIPTION

[0033] Although certain configurations and examples are disclosed herein, the subject matter extends beyond the examples in the specifically disclosed configurations to

other alternative configurations and/or uses, and to modifications and equivalents thereof. Thus, the scope of the claims appended hereto is not limited by any of the particular configurations described below. For example, in any method or process disclosed herein, the acts or operations of the method or process may be performed in any suitable sequence and are not necessarily limited to any particular disclosed sequence. Various operations may be described as multiple discrete operations in turn, in a manner that may be helpful in understanding certain configurations; however, the order of description should not be construed to imply that these operations are order-dependent. Additionally, the structures, systems, and/or devices described herein may be embodied as integrated components or as separate components. For purposes of comparing various configurations, certain aspects and advantages of these configurations are described. Not necessarily all such aspects or advantages are achieved by any particular configuration. Thus, for example, various configurations may be carried out in a manner that achieves or optimizes one advantage or group of advantages as taught herein without necessarily achieving other aspects or advantages as may also be taught or suggested herein.

[0034] Certain embodiments described herein provide methods to determine the positions of multiple wells (e.g., primary and secondary wells) using a high-accuracy multi-dimensional indexed Earth's rate gyroscope in conjunction with magnetic measurements. Certain embodiments may be used in various applications, including but not limited to, twin wells for steam assisted gravity drainage (SAGD), in-fill drilling, target interceptions, coal bed methane (CBM) well interceptions, relief well drilling, syngas well interceptions, river crossings, and many others. Certain embodiments described herein overcome the limitations of multi-well positioning that uses only standard magnetic ranging, but may equally apply to sonic, acoustic, radar, thermal, gravity and ranging that uses any part of the electromagnetic spectrum.

[0035] Certain embodiments described herein advantageously increase safety and reduce costs associated with all ranging including magnetic ranging at all angles of drilling by using gyro-assisted magnetic ranging which combines information obtained from measurement while drilling (MWD) and gyro while drilling (GWD) surveying. Gyro-assisted magnetic ranging can eliminate the need to run wireline conveyed gyros, thereby saving considerable expense. Gyro-assisted magnetic ranging can allow data to be collected

frequently while the drilling progresses, which can reduce (e.g., minimize) the risk of unintentionally intercepting the first wellbore without slowing the drilling process. Gyro-assisted magnetic ranging can be used in conjunction with rotary steerable drilling to automate the drilling process by reducing the role of a human operator in controlling (e.g., steering) the drill string while drilling the second wellbore. Additionally, using gyro-assisted magnetic ranging can provide more accuracy and flexibility in sidetrack trajectories since any attitude is available (e.g., there is no longer a need to steer by inclination only), thereby improving efficiency in drilling operations. For example, a passive MWD ranging system and method can use both the output of MWD magnetic sensors and the directional information calculated from an all-inclination GWD system. Certain such systems and methods can allow the calculation of the spatial relationship (e.g., distance and direction) between the second wellbore and the first wellbore, even at or near 90 degrees inclination. In such configurations in which the second wellbore and the first wellbore are at or near 90 degrees inclination and are not parallel to one another, a high inclination gyro can be used to calculate the azimuth for passive ranging calculations. In certain circumstances, an electromagnetic target is placed in the first wellbore for active ranging. For passive ranging, a permanent magnet target can be placed in the first wellbore. In certain other circumstances in which a target cannot be placed in the first wellbore, a single entry ranging technique can be used, which utilizes passive ranging from the detected remnant magnetization in the first (e.g., target) wellbore casing (e.g., from previous MPI magnetism). Alternatively, active AC magnetic ranging in which an AC current is generated in the target well using an electromagnet in the drilling well may be used (see, e.g., US2004/0069721A1). Besides being used to achieve an intersection of the second wellbore with the first wellbore, the systems and methods described herein can also be used to avoid intersection by allowing the positional relationship between the second wellbore and the first wellbore to be continuously monitored until the collision risk has passed.

[0036] Accurate wellbore positioning information at all angles can advantageously be provided by a gyroscopic system (e.g., a multi-dimensional Earth's rate gyroscope; a three-dimensional indexed Earth's rate gyroscope) which can provide measurements with errors much less than those from magnetic survey systems. Even so, all instruments in a wellbore (e.g., a bottom-hole assembly or BHA) may suffer from some

misalignment due to the tortuosity of the wellbore or due to the lack of survey density in a tortuous wellbore. See, e.g., "Continuous Direction and Inclination Measurements Lead to an Improvement in Wellbore Positioning," E.J. Stockhausen, W.G. Lesso, SPE/IADC 79917, 19 Feb 2003. Magnetic survey instruments also may be adversely affected by magnetic interference from the BHAs, adjacent wellbores, magnetic formations, magnetic mud, and magnetic storms.

[0037] As an example of the effects of errors in these measurements, consider a "well twinning" scenario in which a second wellbore 40 (e.g., a drilling well) is drilled to be generally parallel to a first wellbore 10 (e.g., a target well). It is common practice in well twinning to define at least one target box 50 to be intercepted by the second wellbore 40, with the target box 50 positioned in a production target region and spaced away from the first wellbore 10. Figure 1 schematically illustrates an example target box 50 in a cross-sectional view in a plane generally perpendicular to a first wellbore 10 (e.g., a target well) and to a second wellbore 40 (e.g., a drilling well) generally parallel to the first wellbore 10. The absolute position of the first wellbore 10 can be unimportant. The target box 50 can follow the profile (e.g., trajectory) of the first wellbore 10, paralleling the first wellbore 10 along its length. Target sizes may vary and Figure 1 schematically illustrates an example target box 50 that is 1 meter in a high side direction by 2 meters in a right side direction, and offset from the first wellbore 10 by 5 meters in the high side direction and by 1 meter in the right side direction to allow for the possibility of any re-drills. The target box 50 is a relative target, relative to the first wellbore position. If centered, as a result of a 0.3 degree azimuth error, the second wellbore 40 could drift out of the 1 meter by 2 meters target box 50 over a measured depth of approximately 190 meters.

Ranging Systems and Methods

[0038] A residual error can grow with distance in the absolute position of multiple wellbores, so ranging systems and methods can be used to provide the relative position of one wellbore related to the other or to provide the range (e.g., distance) between the two wellbores.

[0039] Some existing ranging techniques use magnetism as a method to determine the position of another wellbore. These magnetic ranging techniques can include active ranging (e.g., using a magnetic field generated, either AC or DC, by an electromagnet

within the first wellbore), and passive ranging (e.g., using an existing magnetic field). See, e.g., "Surveying of Subterranean Magnetic Bodies from an Adjacent Off-Vertical Borehole," F.J. Morris, R.L. Waters, G.F. Roberts, U.S. Pat. No. 4,072,200, Feb 7 1978; "Downhole Combination Tool," R.L. Waters, et al., EP Pat. No. 0366567, 30.10.89; "Method of Determining the Coordinates and Magnetic Moment of a Dipole Field Source," B.M. Smirnov, *Izmeritel'naya Tekhnika*, No. 6, June 1990.

[0040] In active magnetic ranging, one or more electromagnets 60 may be used as a magnetic field source in the first wellbore 10 (e.g., target well). Thus, active ranging can utilize access to the first wellbore 10. Figure 2A schematically illustrates an example electromagnet 60 with its magnetic field 62 shown by magnetic flux lines. The example electromagnet 60 can be positioned in the first wellbore 10 (e.g., target well) and can output a DC magneto-static field in the first wellbore 10 in response to a current flowing through the electromagnet 60. Figure 2B schematically illustrates an example "extended range magnetic tool" (XMT) comprising an electromagnet 60 compatible with certain embodiments described herein. The example tool of Figure 2B is separated into three sections (e.g., sondes 60a, 60b, 60c) which can be coupled together and can be coupled to a wireline cable head (e.g., using a standard Gearhart connection as a cable head adapter) to be inserted into the first wellbore. An example XMT compatible with certain embodiments described herein is available from TSL Technology Ltd. of Ropley, Alresford, Hampshire, United Kingdom.

[0041] Figure 3A schematically illustrates an example cross-sectional view of the cross-axial magnetic flux pattern in a plane generally perpendicular to the first wellbore 10 (e.g., target well) and to the second wellbore 40 (e.g., drilling well). Figure 3B shows a magnetic map of the magnetic field magnitude (in gauss) of the XMT of Figure 2B in a horizontal plane perpendicular to a longitudinal axis of the XMT. This magnetic field 62 may be detected by standard or adapted (rescaled) magnetometers, which can be included as part of a MWD sensor module or as part of a ranging-dedicated survey package in the BHA (e.g., between a steering mechanism and a drill bit of a rotary steerable drilling tool) of the second wellbore 40 (e.g., the drilling well or the well being drilled). Due to the axially symmetrical nature of the magnetic field 62 around the electromagnet 60 of the first wellbore 10, it is possible to determine the distance of the magnetometers in the second wellbore 40 to the electromagnet 60 from the intensity of the field and the magnetic flux's axial angle, as

these two measurements are unique at a particular distance. The direction to the electromagnet 60 can be determined from the cross-axial component of the magnetic field 62 since the cross-axial component is aligned towards or away from the electromagnet 60. For example, as shown in Figures 2A, 3A, and 3B, the magnetic field 62 is generally cylindrically symmetric about the long axis of the electromagnet 60 (e.g., the magnetic field intensity and angle have the same values along a circle centered on the electromagnet 60), and the magnetic field angle (e.g., the angle θ of the magnetic flux lines with respect to the long axis of the electromagnet) and the magnetic field intensity are dependent on the radial distance from the electromagnet 60 and on the position of the plane perpendicular to the long axis. The cross-axial components (H_{xi} , H_{yi}) of the magnetic field 62 can be used to determine the radial distance of the magnetometers relative to the long axis of the electromagnet 60 and the position of the magnetometers along the long axis of the electromagnet 60.

[0042] This technique can be used in applications in which the second wellbore 40 is drilled to be parallel to the first wellbore 10 (e.g., well twinning for SAGD), for applications in which the second wellbore 40 is intended to avoid the first wellbore 10, or for applications in which the second wellbore 40 is intended to intercept the first wellbore 10 (e.g., horizontal to vertical interception, such as in the case of CBM the electromagnet may be lowered down the near vertical target well). For example, an electromagnet 60 can be pushed along the first wellbore 10 (e.g., target well) using a tractor, coil tubing, or other means. The electromagnet 60 can be positioned in the center of a casing joint of the first wellbore 10, rather than near the ends of the casing joint, since the casing collars at the joint ends have substantially more metal and can therefore distort the magnetic field in an asymmetric way. Thus, the magnetic ranging surveys can be taken away from the collars to prevent (e.g., reduce, minimize) this distortion. For example, Figure 4 is a schematic diagram of the magnetic field 62 of an example electromagnetic target between two casing joints of a target well. Standard methods include the use of two survey measurements taken at each casing joint, one with the electromagnet 60 energized in a positive mode and another with the electromagnet 60 energized in a negative mode. The difference between the readings can provide a measurement of two times the strength of the magnetic field 62 from the electromagnet 60. In other situations, the survey measurements taken at each casing joint can include one with the electromagnet 60 energized or “on” and another with the

electromagnet 60 not energized or "off". However, there can be residual magnetic interference in the casing (e.g., from previous magnetic particle inspection or MPI of the casing, or by magnetization of the casing due to previous uses of the electromagnet 60) that can distort the null field. The survey measurements can be taken about every 11 to 13 meters (e.g., the casing joint length) along the second wellbore 40, as indicated in Figure 4. The time for taking such survey measurements depends on the transmission system used. For example, if electromagnetic (EM) pulse telemetry is used, the time for transmitting the information from the survey measurements to an above-surface location can be a significant fraction of the total time for taking a mud pulsed survey. However, the faster technique of electromagnetic telemetry can significantly shorten the total time for taking the survey.

[0043] The first wellbore 10 may be cased with steel or other materials that can affect the magnitude and/or direction of the magnetic field 62. For example, due to its magnetic permeability, the effect of steel can be to absorb some of the magnetic field 62. See, e.g., "Method and Apparatus for Measuring Distance and Direction by Movable Magnetic Field Source," A.F. Kuckes, Vector Magnetics, Inc., U.S. Reissue Pat. No. 36,569, U.S. Pat. No. 5,485,089, filed 8 Oct 1993. In addition, the position of the electromagnet 60 in the casing, if non-centered, may cause an asymmetry in the magnetic field 62 outside the casing. This effect can be difficult to model for, hence it can be a source of error in the results especially with weak electromagnets.

[0044] These detrimental effects can be somewhat negated in active ranging by the use of a very powerful XNT type electromagnet 60. For example, a sufficiently powerful electromagnet 60 can magnetically saturate the casing and can thereby create a useful effect. A magnetically saturated casing may not absorb nor inhibit the magnetic flux, so the magnetic flux can therefore pass through uninhibited. There may be some reduction in the strength of the near field due to the absorption from the casing, amounting to a reduction in the magnetic field magnitude of a few percent. The effect can also slightly increase the pole separation that is observed outside the casing, which may enhance the far field. Casing diameter, thickness, and the permeability of the casing material may all have an influence as is understood by persons skilled in the art. Casings often can have collars to reinforce the thin walls at the threads where adjacent casing sections are coupled to one another. Such collars can create a distortion in the symmetry of the magnetic field 62 (e.g., lack of axial

symmetry in the magnetic field 62) created by the electromagnet 60. Although this effect can be considered to be local, near field measurements can be avoided around these areas. In addition, it can be helpful to ensure that the electromagnet 60 is positioned at the central axis of the casing joint to avoid erroneous ranging results at this position due to the cross axial component being near zero.

[0045] Another technique that can be used for active magnetic ranging of adjacent wells is the use of permanent magnets placed in a bit sub. See, e.g., "Rotating Magnetic Ranging – A New Guidance Technology," A.G. Nekut, A.F. Kuckes, R.G. Pitzer 8th SPE, One Day Conference on Horizontal Well Technology, 7.11.2001; "Rotating Magnet for Distance and Directional Measurements from a First Borehole to a Second Borehole," A.F. Kuckes, U.S. Pat. No. 5,589,775. These permanent magnets can rotate with the bit (within the second wellbore 40) and can create a low frequency (e.g., at the revolution per minute of the bit) alternating magnetic field 62. The maximum amplitude of the signal (measured from within the first wellbore 10) is when the magnets are coplanar to the cross-axial component of the first wellbore 10. From this maximum amplitude, it can be possible to derive the distance between the second wellbore 40 and the first wellbore 10.

[0046] When the measured maximum negative magnetic field magnitude is subtracted from the measured maximum positive magnetic field magnitude, the resultant vector can be expressed as an angle on the cross-axial (target) plane. This vector can indicate the direction to the second wellbore 40. A distance and strength of the source can be derived by using the half-height-width of the wave and a gradient of the overall ellipse of the waveforms can indicate distance. See, e.g., "A Gyro-Oriented 3-Component Borehole Magnetometer for Mineral Prospecting, With Examples of its Application," W. Bosum, D. Eberle, H.J. Rehli, "Geophysical Prospecting 36," pp. 933-961, 1988; "Case Histories Demonstrate a New Method for Well Avoidance and Relief Well Drilling," G. McElhinney, R. Sognnes, B. Smith, SPE/IADC 37667. It is noted that the signal can be much weaker inside a casing.

[0047] Other active magnetic ranging techniques may include devices that output an AC electromagnetic field from the second wellbore 40 to create a current in the first wellbore 10 (e.g., the target wellbore). As current flows through the first wellbore casing, along the BHA and formation boundaries, it can thus create other magnetic fields. The BHA

current and magnetism is usually fairly constant and may be removed by rotation shots. Formation boundary effects, non-homogeneous formations and anisotropy can be more problematic to solve for. Generally, the more homogeneous the formations are, the easier it is to model these effects out.

[0048] A technique using a single wire run in the first wellbore 10 and anchored at its foot can be used. A DC current can be passed through the wire to generate a circular magnetic field 62 in cross section. When the current dissipates through the anchor point into the casing, an unknown magnetic field can be created in the opposite direction to the magnetic field created by the wire. The magnitude of the current and the distance along the casing the current travels are dependent on the conductivity of the casing versus the conductivity of the formation. In high resistive, low conductive formations (e.g., like the oil sands), this reverse current generates a reverse magnetic field that can travel further up the casing, having a detrimental effect on results above the anchor point.

[0049] The aforementioned active magnetic ranging techniques can have limitations that can cause relative and absolute positional errors, which can be compounded by a reaction to these errors. For example, as mentioned in "A Gyro-Oriented 3-Component Borehole Magnetometer for Mineral Prospecting, With Examples of its Application," W. Bosum, D. Eberle, H.J. Rehli, "Geophysical Prospecting 36," pp. 933-961, 1988 and "Case Histories Demonstrate a New Method for Well Avoidance and Relief Well Drilling," G. McElhinney, R. Sognnes, B. Smith, SPE/IADC 37667, there can be an issue determining the solution for the 180 degree ambiguity, which can result in the position of the second wellbore 40 being misinterpreted as left of the first wellbore 10 instead of right, or vice versa. This ambiguity may result in the second wellbore 40 being steered in the wrong direction and leading to an exit from the target box 50. There is often some delay in realizing what has happened, and the second wellbore 40 may further drift away from the target box 50. As this drift is corrected, the second wellbore 40 may no longer retain a straight profile which may lead to problems running casings, liners, etc. along the second wellbore 40.

[0050] It is possible to reduce the ambiguity by taking a single reading from the source and subtracting the Earth's magnetic field from that reading. However, in order to determine the components of the Earth's magnetic field (as seen along the axis of the magnetometers), three things/indicia/metrics may be useful, including: the strength of the

field; the dip of the field; and the direction of the field with respect to the long axis of the probe. The direction of the field, at times, can be problematic, but can be assumed by fitting the ranging data (e.g., changing the azimuth of the Earth magnetic field), to change the ranging data. This fitting can be done by iteration to provide a close fit. However, previous assumptions can easily affect this result, affecting the absolute and relative positions of the wellbore being drilled, and so multiple historical azimuths may be adjusted to produce a resultant survey that can be used. Derivation of the azimuths using magnetic survey data can be adversely affected by residual magnetic particle inspection (MPI) magnetism in the first wellbore 10, residual magnetism left in the core of the electromagnet 60, magnetism induced in the casing from the electromagnet 60, and BHA magnetism. These contributions to the residual magnetism can deflect the magnetically derived azimuth and can give a misleading Earth's magnetic field removal that could lead to incorrect absolute and relative positions for the second wellbore 40.

[0051] These magnetic ranging techniques can also suffer from increasing error with distance between the first wellbore 10 and the second wellbore 40, since as the size of the signals decreases, the noise-to-signal ratio increases. As a result, positional uncertainty can be created, leading to incorrect steering of the second wellbore 40.

[0052] Magnetic ranging techniques can also have difficulty in determining the 180 degree, left right issue, as mentioned above. If the Earth's magnetic field could be well understood, then it could be simple to remove the Earth's magnetic field from a single reading to derive the magnetic vector from the target. To derive how the Earth's magnetic field affects each magnetometer, it can be advantageous to have accurate knowledge of each of the following: Earth's total magnetic field; the magnetic dip angle M_{Dip} ; and azimuth. The Earth's total magnetic field and M_{Dip} can be derived from models like the British Geological Survey (BCS) Global Geomagnetic Model (BGGM), High Definition Geomagnetic Model (HDGM) of the National Geophysical Data Center of the National Oceanic and Atmospheric Administration (NOAA), etc. These models, however, fail to take into account all local anomalies, possibly resulting in errors of about 900 nanoTesla in the total magnetic field and about 0.7 degrees in M_{Dip} (at about 70 degrees latitude). Also, the azimuth may be deflected by magnetism from the first wellbore and the BHA. The total magnetic field and M_{Dip} can be measured at or near the location of the second wellbore 40, which generally gives good

results. The azimuth can be derived down hole as it is the direction in which the survey tool is pointing with respect to the field it senses. However, because the field is deflected, it may not be a true azimuth and therefore the backed out interference field would be in error. These effects may be a problem as algorithms like multi-station analysis that may be used to correct for BHA interference, generally assume the presence of a single source of interference. When the second wellbore 40 (e.g., a drilling well) leaves the build section to drill the lateral section, it is subjected to interference from the BHA and the first wellbore 10 (e.g., a target well). These two sources can make it difficult to solve the interference effects and the derivation of the azimuth, thereby introducing an error in the derivation of the relative position of the second wellbore 40. This problem can be solved when the azimuth is derived from high accuracy gyroscopic measurements.

Gyro-assisted magnetic ranging systems and methods

[0053] Figure 5A is a flow diagram of an example method 100 to determine a distance, a direction, or both between an existing first wellbore 10 and at least one sensor module 20 of a drill string 30 within a second wellbore 40 being drilled in accordance with certain embodiments described herein. In an operational block 120, the method 100 comprises using the at least one sensor module 20 to measure a magnetic field and to generate at least one first signal indicative of the measured magnetic field. In an operational block 140, the method 100 further comprises using the at least one sensor module 20 to gyroscopically measure an azimuth, an inclination, or both of the at least one sensor module 20 and to generate at least one second signal indicative of the measured azimuth, inclination, or both. In an operational block 160, the method 100 further comprises using the at least one first signal and the at least one second signal to calculate a distance between the existing first wellbore 10 and the at least one sensor module 20, a direction between the existing first wellbore 10 and the at least one sensor module 20, or both a distance and a direction between the existing first wellbore 10 and the at least one sensor module 20. In certain embodiments, the method 100 further comprises using the calculated distance, the calculated direction, or both to control the drill string 30 (e.g., a rotary steerable drill string). For example, at least one control signal can be generated (e.g., automatically) in response to the calculated distance, the calculated direction, or both, and the at least one control signal can be transmitted to a steering mechanism of the drill string 30.

[0054] Figure 5B is a flow diagram of an example method 200 for controlling a drill string 30 spaced from an existing first wellbore 10, the drill string 30 drilling a second wellbore 40, in accordance with certain embodiments described herein. In an operational block 210, the method 200 comprises receiving at least one first signal indicative of a magnetic field measured by at least a first sensor module 22 of the drill string 30. The first sensor module 22 comprises at least one magnetometer. In an operational block 220, the method 200 further comprises receiving at least one second signal indicative of an azimuth, an inclination, or both measured by at least a second sensor module 24 of the drill string 30. The second sensor module 24 comprises at least one gyroscopic sensor. In an operational block 230, the method 200 further comprises calculating a distance between the existing first wellbore 10 and the first sensor module 22, a direction between the existing first wellbore 10 and the first sensor module 22, or both a distance and a direction between the existing first wellbore 10 and the first sensor module 22. In an operational block 240, the method 200 further comprises generating, in response to at least one of the calculated distance and the calculated direction, at least one control signal to be transmitted to a steering mechanism of the drill string 30. The method 200 can be performed by a computer system (e.g., a microprocessor) in operational communication with the drill string 30 (e.g., with at least the first sensor module 22, at least the second sensor module 24, and the steering mechanism of the drill string 30).

[0055] In certain embodiments, systems and methods can be used to advantageously address the problems or limitations of magnetic ranging systems and methods by using at least one sensor module comprising at least one gyroscope ("gyro") to provide information (e.g., information regarding the azimuth) to supplement information provided by the magnetic ranging (e.g., information provided by at least one sensor module comprising at least one magnetometer). Certain such embodiments combine the use of at least one gyro with at least one of the magnetic ranging systems and methods described above to advantageously negate some of the problems described above.

[0056] In certain embodiments, the gyro-assisted magnetic ranging systems and methods described herein may allow accurate relative and absolute spatial positions to be acquired from the ranging data (e.g., providing definitive results while avoiding complex and imprecise calculations based on noisy magnetic measurements alone to remove Earth's field

effects). In certain embodiments, comparing the gyro-derived information regarding azimuth and inclination to the magnetometer-derived information can be used to identify erroneous contributions to the magnetometer measurements (e.g., due to going out of calibration, magnetic contributions from ferrous formations containing magnetite or basaltic layers or from geothermal wells in volcanic formations). In addition, when using an axial magnetometer to provide information about the approach of an existing wellbore, comparing the gyro-derived information to the magnetometer-derived information can be used to optimize the magnetic ranging process by reducing (e.g., avoiding, minimizing) the effects of axial magnetization from the drill string itself along the tool axis, thereby allowing for ranging while drilling.

[0057] In certain embodiments, the gyro-assisted magnetic ranging systems and methods described herein may provide gyro-derived information can be used to provide a definitive survey of the wellbore 40 immediately after tripping the drill string 30 out of the wellbore 40. In contrast, using magnetic ranging- or MWD-derived information alone can take two to three days of analysis to generate a full survey which includes both azimuth and inclination. In certain embodiments, back calculations and iterative techniques may be used to estimate the wellbore position.

[0058] In certain embodiments, the gyro-assisted magnetic ranging systems and methods described herein can be used to automate rotary steerable drilling (e.g., by reducing the role of a human operator in steering the drill string 30 while drilling the second wellbore 40 as compared to conventional magnetic ranging techniques). The at least one sensor module 20 can comprise a MWD sensor pack of a rotary steerable drilling tool. For example, the at least one sensor module 20 can comprise at least one gyro module and at least one magnetometer module, or a first sensor module 22 comprising at least one gyro and a second sensor module 24 comprising at least one magnetometer. The at least one sensor module 20 can be positioned in a wide range of locations along the drill string 30 (e.g., below the steering mechanism, in the steering mechanism, or above the steering mechanism) and can be used to provide the measurements to be used as part of the gyro-assisted magnetic ranging. For example, the at least one sensor module 20 can be above the steering mechanism by a distance between 40 meters and 70 meters. For another example, the at least one sensor module 20 positioned below the steering mechanism in proximity to the drill bit (e.g.,

directly behind the drill bit, above the drill bit by a distance between 10 meters and 15 meters) in the rotary steerable tool can be used as part of the gyro-assisted magnetic ranging. In certain embodiments, using at least two magnetic sensor modules (e.g., one sensor module positioned above the steering mechanism and another sensor module positioned below the steering mechanism) can provide information on the angle of approach of the drill string 30 to the existing first wellbore 10 (see, e.g., U.S. Pat. Nos. 8,095,317 and 8,185,312). In certain embodiments, using at least two magnetic sensor modules can provide information to be used to reduce the effect of bias created by magnetic interference from BHA components. For example, measurements taken with a first magnetic sensor module near a ferromagnetic BHA component (e.g., sufficiently near to provide measurements affected by a magnetic field of the BHA component) and a second magnetic sensor module spaced away from the ferromagnetic BHA component (e.g., sufficiently away to provide measurements not affected by a magnetic field of the BHA component) can be subtracted from one another to provide information regarding residual biases due to the magnetic field of the BHA component.

[0059] Certain embodiments described herein are configured to drill a predetermined well path while locating a target well with a reduced role of a human operator (e.g., automatically). The predetermined well path can be selected to keep a predetermined distance between the target well and the well being drilled, to intercept the target well at a predetermined position (e.g., true vertical depth) or formation, or to find and stay within a formation. In certain embodiments, the gyro-assisted magnetic ranging systems and methods described herein can be used in conjunction with active magnetic ranging to automate rotary steerable drilling. In certain other embodiments, the gyro-assisted magnetic ranging systems and methods described herein can be used in conjunction with passive ranging (e.g., detection of remnant magnetization in the target well casing, for target well interception or target well avoidance) to automate rotary steerable drilling.

[0060] In certain embodiments, the gyro-assisted magnetic ranging systems and methods described herein can provide more accurate detection or warnings of approaching a target well. For example, while magnetic ranging alone may give a warning of the second wellbore 40 approaching the first wellbore 10, the gyro measurements can be used to generate values of the azimuth and inclination of the second wellbore 40. These values can be compared to those of previous surveys of the first wellbore 10 to determine a proximity

between the first wellbore 10 and the second wellbore 40. In addition, the gyro measurements can be used to estimate the magnetic fields expected to be detected at the particular azimuth and inclination determined by the gyro sensor module 24. Deviations or distortions between the expected magnetic fields and the measured magnetic fields can be indicative of the existence of the first wellbore 10 in proximity to the second wellbore 40. For example, deviations of the measured magnetic field magnitude and dip angle (e.g., calculated using equations as disclosed more fully below) and the expected values of these same quantities (e.g., from the Earth's magnetic field) can be used to indicate the existence of the first wellbore 10 in proximity to the second wellbore 40.

[0061] In certain embodiments, the gyro-assisted magnetic ranging systems and methods described herein include a gyro (e.g., a gyro having small errors at high angles of inclination), in conjunction with magnetic survey instruments. Certain such embodiments may overcome the problem of poorly derived azimuths and Earth's magnetic field removal in conventional ranging systems. Certain such embodiments can advantageously provide more accurate ranging data for the relative position of the second wellbore 40. In addition, the gyro data may give a more reliable and accurate absolute wellbore position.

[0062] In certain embodiments, by using a gyro, the gyro-assisted magnetic ranging systems and methods described herein may advantageously reduce the number of ranging survey measurements to be taken as compared to magnetic ranging systems and methods that do not utilize gyro measurements. By sending inclination and azimuth measurements to the surface to calculate steering commands, the gyro-assisted magnetic ranging systems and methods described herein may reduce the number of high resolution magnetometer measurements (e.g., 100 nanotesla) transmitted to the surface for the ranging calculations, as compared to conventional MWD-based ranging systems and methods.

[0063] For example, the number of magnetic ranging survey measurements taken can be reduced (e.g., to one per casing joint), thereby saving time and allowing faster well completion. For example, the duration of the magnetic ranging process at each station (e.g., taking six high-resolution magnetometer and accelerometer measurements at each station, with the stations spaced from one another by about 11-13 meters) can be 8 minutes (assuming mud pulse telemetry), resulting in a total ranging time using magnetic ranging alone of 96 minutes for each 100 meters drilled. By using gyro measurements in

combination with magnetic ranging measurements to provide information regarding azimuth and inclination at intervening stations (e.g., two relatively low-resolution measurements of 2 minutes duration each), the number of magnetic survey measurements can be reduced (e.g., to one per 100 meters). Thus, the total time for which drilling is stopped for the gyro-assisted magnetic ranging technique then can be about 24 minutes per 100 meters drilled, which is about one hour less for every 100 meters drilled using magnetic ranging alone. Besides saving time during drilling, by reducing the period of time during which the drill string 30 is stopped for taking measurements (e.g., fewer long-duration magnetic ranging measurements being made), certain such embodiments can reduce the probability of the drill string 30 getting stuck in the wellbore 40. Note that the benefits of time saved and reduced probability of getting stuck for gyro-assisted magnetic ranging as compared to magnetic ranging alone using electromagnetic ranging relate largely to the time taken to transmit data to the surface, which would be less in configurations in which faster communication is possible (e.g., the time per magnetic ranging measurement is significantly smaller for electromagnetic telemetry than for mud pulse telemetry).

[0064] To illustrate this aspect, Figures 6A schematically illustrates the positions of a number of standard magnetic ranging survey measurements to be taken along a target box 50 that is 570 meters long and Figure 6B schematically illustrates the positions of a fewer number of gyro-assisted ranging survey measurements to be taken along the target box 50. As shown in Figure 6A, because of the larger reference errors in magnetic ranging, many magnetic ranging survey measurements (at positions denoted by vertical arrows along the target box 50) are to be taken along the target box 50 in an attempt to keep the second wellbore 40 within the target box 50. In contrast, as shown in Figure 6B, using gyro-assisted magnetic ranging, the number of survey measurements to be taken along the target box 50 (at positions denoted by vertical arrows along the target box 50) can be fewer (e.g., by approximately a factor of 16) than in Figure 6A. For example, if a gyro has a reference error of 0.3 degree, then it is possible the second wellbore 40 would leave the target box 50 after 190 meters, assuming no ranging error. With the inclusion of a gyro, the influence of the ranging error can be reduced (e.g., by only performing gyro-assisted ranging survey measurements when the uncertainty reaches the edge of the target box 50). For example, allowing for a horizontal positional ranging error of about ± 0.25 meter (at 5 meters), the

second wellbore 40 could leave the target box 50 after 143 meters has been drilled. It may be expedient to allow for other errors and so a 120 meter ranging interval could be optimum, thereby saving time and being less problematic than the standard ranging survey practice for surveying every joint (about every 10-13 meters). Certain embodiments described herein with the inclusion of a gyro could reduce the ranging survey requirement by about 90%.

[0065] In addition, by providing azimuth and inclination information, the gyro measurements can be used to allow the Earth's magnetic field to be removed from the ranging calculations. For example, once the azimuth and inclination of the downhole portion are known from the gyro measurements, reference information (e.g., a model; a database) regarding the Earth's magnetic field at various azimuths and inclinations can be accessed, and the measured azimuth and inclination can be used to determine a contribution from the Earth's magnetic field to the measured magnetic field that can be expected at the measured azimuth and inclination. This expected contribution to the measured magnetic field can then be subtracted from the measured magnetic field to provide a corrected measured magnetic field to be used in the ranging calculations, as described more fully below.

[0066] Gyro-assisted magnetic ranging can be used to drill infill wells that are positioned between existing well pairs, and to re-drill wells positioned adjacent to the drilled second well. Infill wells are when the lateral sections are often about 100 meters apart, and another well is drilled in between to aid production or injection. Re-drills are often used when wells have sanded up, steam jumped, or other causes. When either drilling infill wells or re-drilling wells, it can be advantageous to have access to an accurate absolute position of the existing wells. If the absolute position is accurate, then the risk of collision can be avoided (e.g., reduced) and the recovery from the reservoir can be optimized. As previously described, magnetic surveys may be adversely affected by interference from BHAs, other wells, magnetic storms, etc. Such interference may create large uncertainties in the absolute wellbore position. In certain embodiments described herein, use of a gyro in ranging systems and methods does not suffer from such issues and can provide increasingly accurate absolute and relative wellbore positions. Also, the less frequent use of the electromagnet means the casing in the first wellbore may be less magnetized and therefore less likely to distort the electromagnetic field.

Determining the Interference Field Due to Proximity to Another Wellbore

[0067] In certain embodiments, gyro-assisted magnetic ranging uses a determination of the interference field due to the proximity of the wellbore being drilled to another previously-drilled wellbore. At least one magnetometer module of the at least one sensor module 20 can be subject to the Earth's magnetic field plus an interference field which, for the purpose of the following analysis, can be assumed to be wholly the result of proximity of the at least one magnetometer module to a nearby wellbore (e.g., the first wellbore 10; the target wellbore). For example, in passive ranging, the remnant magnetization of at least one casing or casing joint of the target wellbore can contribute to the interference field. In another example, in active ranging, a magnetic field created within the target wellbore (e.g., using an electromagnet such as a solenoid) can contribute to the interference field, in addition to any remnant magnetization.

[0068] The components of the magnetic field sensed by the at least one magnetometer module (H_{xr} , H_{yr} , H_{zr}) can be expressed as the sum of the components of the Earth's magnetic field (H_x , H_y , H_z) and the components of the interference field (H_{xi} , H_{yi} , H_{zi}) as follows:

$$\begin{aligned} H_{xr} &= H_x + H_{xi} \\ H_{yr} &= H_y + H_{yi} \\ H_{zr} &= H_z + H_{zi} \end{aligned}$$

The ranging calculations can be based upon estimates of the interference field, the components of which can be determined by subtracting the components of the Earth's magnetic field from the components of the magnetic field measured by the at least one magnetometer module:

$$\begin{aligned} H_{xi} &= H_{xr} - H_x \\ H_{yi} &= H_{yr} - H_y \\ H_{zi} &= H_{zr} - H_z \end{aligned}$$

[0069] In certain embodiments, the components of the Earth's magnetic field to be subtracted from the components of the measured magnetic field can be derived using knowledge of the total Earth's magnetic field (H_e), the magnetic dip (D), and the orientation of the drilling tool as defined by its azimuth (A), inclination (I), and high side rotation (R), viz.:

$$\begin{aligned}
H_x &= H_e(\cos D \cos A \cos I \sin R - \sin D \sin I \sin R + \cos D \sin A \cos R) \\
H_y &= H_e(\cos D \cos A \cos I \cos R - \sin D \sin I \cos R - \cos D \sin A \sin R) \\
H_z &= H_e(\cos D \cos A \sin I + \sin D \cos I)
\end{aligned}$$

[0070] Values of the inclination and high side rotation can be obtained from accelerometer measurements by the at least one sensor module 20 (e.g., by one or more accelerometers), values of the azimuth can be obtained from gyroscopic measurements by the at least one sensor module 20 (e.g., by one or more gyros), and values of the total Earth's magnetic field and the magnetic dip can be known.

[0071] Note that the azimuth of the drilling tool is used to define the Earth's magnetic field effect on the magnetometers. If the azimuth is not well known (e.g., guessed), then the results of H_x , H_y , and H_z will be in error. Any results that follow that are used to determine ranging data (e.g., distance and direction to the target well), such as the total interference field (H_i), the magnetic inclination (M_i), and the direction of the interference vector (D_v), will also be in error. If the azimuth is well known (e.g., from an accurate gyro measurement), then the resulting ranging data should also be accurate. Furthermore, if any of these values are not well defined, then the computed components of the Earth's magnetic field (H_x , H_y , H_z) will be in error, and it follows that any ranging calculations carried out based on the estimated interference field will also be in error.

[0072] For ranging, the following values can be calculated using the components of the estimated interference field (H_{xi} , H_{yi} , H_{zi}). The total interference field (H_i) can be expressed as: $H_i = (H_{xi}^2 + H_{yi}^2 + H_{zi}^2)^{1/2}$. The magnetic inclination (M_i) with respect to the longitudinal axis of the tool can be expressed as the angle: $M_i = \text{ATan}[(H_{xi}^2 + H_{yi}^2)^{1/2} / H_{zi}]$. The direction of the interference vector (D_v) with respect to the projection of the longitudinal axis of the tool into the horizontal plane can be expressed as:

$$D_v = \text{ATan}[((G_x^2 + G_y^2 + G_z^2)^{1/2} * (H_{xi} * G_y - H_{yi} * G_x)) / (H_{zi}(G_x^2 + G_y^2) + H_{xi} * G_x * G_z + H_{yi} * G_y * G_z)]$$

where G_x , G_y , and G_z are the three orthogonal components of the gravitational vector pointing towards the Earth's center.

[0073] Other effects on the reliability of the interference vector include, but are not limited to, BHA magnetic interference, adjacent wells, magnetic storms, formation effects (e.g., high Fe content, etc.) and noise in the electromagnet system. Some of these effects can be negated (see, e.g., "Location Determination Using Vector Measurements," G. McElhinney, EP Pat. No. 0682269, 12.5.95; "Electromagnetic Array for Subterranean

Magnetic Ranging Operations,” G. McElhinney, R. Moore. US Pat. Appl. Publ. No. 2012/0139530, 7 June 2012. An estimation of these effects, after corrections have been applied, may be a ranging distance error of the order of 10 to 50 centimeters at 5 meters displacement.

[0074] It can be advantageous to correct as many detrimental effects as possible to increase the accuracy of the ranging data. For example, using methods such as Earth’s field monitoring at or near the rig site, multi-station analysis to remove BHA interference, and measuring the BHA interference, pre-run, can be used to supplement the gyro-assisted magnetic ranging systems and methods described herein. Alternative methods, including but not limited to interpolated in-field referencing (IIFR) which takes into account diurnal variations in the magnetic field and uses interpolation between measurements from reference stations located some distance apart to determine field variations at the drill site, may also be employed.

[0075] For BHA interference measurements, an analysis of the electromagnetic vectors can indicate the presence of BHA interference and can be used to help remove its detrimental effect. For example, Figure 7 schematically illustrates a comparison between balanced electromagnetic vectors and unbalanced electromagnetic vectors due to BHA interference (note that Figure 7 omits the contribution from the Earth’s field for clarity). In certain embodiments, the BHA interference contribution can be considered to be a constant, and it can be subtracted from the measured magnetic field to derive the magnetic field due to the electromagnet 60 and the Earth’s field. If there is a BHA interference vector present, then an imbalance in the +/- electromagnetic vector will be measured, as shown in Figure 7. This imbalance can be solved for by removing the BHA interference vector (e.g., to create a balanced +/- electromagnetic vector once the contribution from the Earth’s field has been removed). Various mathematical processes (see, e.g., “Method for Correcting Directional Surveys,” G. McElhinney, EP Pat. No. 0793000, May 14, 1996) may be employed to remove the BHA interference vector. Once the magnetic fields (e.g., electromagnetic vectors) due solely to the electromagnet 60 are determined at a position of the at least one sensor 20, these values can be used as described herein to determine the position of the at least one sensor module 20 within the second wellbore 40 relative to the electromagnet 60 in the first

wellbore 10. This determined position can then be used to steer the drill string 30 in the second wellbore 40 to a predetermined position relative to the first wellbore 10.

Rotary steerable drilling in conjunction with gyro-assisted magnetic ranging surveys

[0076] While the discussion below addresses the drilling of a second wellbore 40 alongside (e.g., parallel) to an existing first wellbore 10, the systems and methods described are equally applicable for the drilling of a second wellbore 40 configured to intercept a first wellbore 10 (e.g., in the event of a blowout). Similar guidance strategies may be adopted for the automation of such a process. For example, gyro-assisted magnetic ranging can be used for the terminal stages of the interception process to reduce the role of a human operator in steering the second wellbore to intersect the first wellbore.

[0077] In certain embodiments, a drilling tool 30 (e.g., a drill string) is controlled (e.g., steered) in response to signals derived from gyro-assisted magnetic ranging survey measurements to follow a desired path (e.g., trajectory). For example, the drilling tool 30 can be steered to drill a second wellbore 40 that follows a course alongside and parallel to an existing first wellbore 10. The desired path of the second wellbore 40 can be controlled to remain within at least one target box 50 that follows the existing first wellbore path at a pre-defined distance (e.g., a fixed distance above, a fixed distance below, a fixed distance left, a fixed distance right) from the first wellbore path. Steering signals (e.g., commands) can be generated to cause the drilling tool 30 to form the second wellbore 40 to follow, and to attempt to intercept, a sequence of target boxes 50 defined at intervals along the first wellbore path. In certain such embodiments (e.g., where bending is applied to a flexible shaft of the rotary steerable tool in proportion to the angle between the tool axis and the target line of sight), the steering signal magnitudes are proportional to the angular differences (e.g., in inclination and azimuth) between the next target line of sight and the orientation of the drilling tool 30. Given knowledge of the coordinates of the drilling tool 30 and the location of the first wellbore 10 in the chosen reference frame, the target line of sight relative to the drilling tool 30 can be updated for each well section.

[0078] In certain embodiments, the second wellbore path may be a predetermined distance (e.g., 3 – 5 meters separation) from the first wellbore path that is sufficiently small such that magnetic ranging is conducted. In certain such embodiments (e.g., when a new well is to be drilled in close proximity to an existing well, such as in the case of SAGD

applications), magnetic ranging is viable and gyro-assisted magnetic ranging can be used to provide information used to achieve the desired second wellbore path (e.g., trajectory). For example, standard survey methods may be used to guide the second wellbore 40 to within range of the first wellbore 10 such that magnetic ranging can be used. Thereafter, a guidance strategy based on a local reference frame defined by the relative separation and orientation of the second wellbore 40 with respect to the first wellbore 10 may be adopted. In certain such embodiments, the drilling tool location with respect to the next target boxes can be updated periodically as new ranging measurements becomes available.

[0079] In certain embodiments, a closed-loop drilling process is used to control (e.g., steer) a drilling tool 30 (e.g., a rotary steerable drill string). For example, a BHA within the second wellbore 40 can comprise a drill bit at an end of the rotary steerable drill string, a first sensor module 22, and a second sensor module 24 spaced from the first sensor module 22 along the rotary steerable drill string in a direction away from the drill bit. The first sensor module 22 can comprise a plurality of rotary steerable sensors (e.g., a plurality of magnetometers, accelerometers, and/or gyros). The second sensor module 24 can comprise a magnetic MWD sensor pack and a gyroscopic GWD sensor pack.

[0080] Figure 8A schematically illustrates an example configuration of a drilling tool 30 configured to drill a second wellbore 40 (e.g., drilling well) along a desired path parallel to and in close proximity to a first wellbore 10 (e.g., target well). The drilling tool 30 comprises a steering mechanism configured to controllably adjust the tool path direction (e.g., direction in which the second wellbore 40 is being drilled) in response to at least one steering signal (e.g., command) from a computer system (e.g., a computer processor mounted on the drilling tool 30 or outside the second wellbore 40). The drilling tool 30 further comprises at least a first sensor pack 22 positioned below the steering mechanism (e.g., in proximity to a drill bit of the drilling tool) and at least a second sensor pack 24 positioned above the steering mechanism (e.g., such that the steering mechanism is between the first sensor pack 22 and the second sensor pack 24).

[0081] Figure 8B is a flow diagram of an example method 400 of drilling a second wellbore 40 (e.g., drilling well) along a desired path parallel to a first wellbore 10 (e.g., target well). The second wellbore 40 can be in close proximity to the first wellbore 10 (e.g., within 3-5 meters). The method 400 can be performed by the computer system of the

drilling tool 30. In an operational block 410, a target position can be defined along a desired path of the second wellbore 40. The target position can be spaced a distance (d) from the current position of the drilling tool 30. In an operational block 420, magnetic ranging measurements relative to the first wellbore 10 and gyroscopic measurements of an azimuth, an inclination, or both of the drilling tool 30 are made, and these measurements are used to determine a distance ($\tilde{s}$) between the current position of the drilling tool 30 and the first wellbore 10. For example, the distance ($\tilde{s}$) can be measured or derived using magnetic ranging measurements using the first sensor module 22, the second sensor module 24, or both the first sensor module 22 and the second sensor module 24 with these magnetic ranging measurements corrected using the gyroscopic measurements as described herein. Magnetic ranging measurements can be used to provide information regarding the distance of the drilling tool 30 (e.g., an end portion of the drill string, the drill bit, the first sensor module 22) from the first wellbore 10 and the direction of the second wellbore path with respect to the first wellbore path.

[0082] In an operational block 430, a distance ($\Delta s = \tilde{s} - s$) between the first wellbore path and the desired path of the second wellbore 40 can be calculated. In an operational block 440, a target sightline angle ($\beta = \arctan \left[\frac{\Delta s}{d} \right]$) with respect to the desired path of the second wellbore 40 can be calculated. In an operational block 450, a tool path direction (α) with respect to the first wellbore path can be measured (e.g., using the first sensor module 22, the second sensor module 24, or both the first sensor module 22 and the second sensor module 24). In an operational block 460, a steering angle ($\gamma = \alpha - \beta$) can be calculated. In an operational block 470, a steering signal (e.g., command) can be transmitted to the steering mechanism (e.g., a shaft bending mechanism, an example of which is described in U.S. Pat. No. 8,579,044) to control the steering mechanism to adjust the tool path direction by the steering angle. In certain embodiments, the steering signal has a magnitude proportional to the steering angle. In an operational block 480, a new target position along the desired path of the second wellbore 40 is defined, the new target position a distance (d) from the current position of the drilling tool 30 (e.g., since the drill string has moved by virtue of drilling the second wellbore 40). The method 400 can further comprise iterating the operational blocks 420-480 (denoted in Figure 8B by the arrow 490).

[0083] Figure 9 schematically illustrates an example measurement of the tool path direction (α) with respect to the first wellbore path using the first sensor module 22 and the second sensor module 24. Using information regarding the distance (h) between the first sensor module 22 and the second sensor module 24, the measured distance ($\tilde{s}_1$) between the current position of the first sensor module 22 and the first wellbore 10, and the measured distance ($\tilde{s}_2$) between the current position of the second sensor module 24 and the first wellbore 10, the tool path direction can be provided by the relation: $\alpha = \arcsin\left(\frac{\tilde{s}_2 - \tilde{s}_1}{h}\right)$. A similar calculation can be performed for a “dogleg” section of the drilling tool 30, given an estimate of the bend of the drilling tool 30 between the first sensor module 22 and the second sensor module 24.

[0084] Figure 10 schematically illustrates an example progression of the drilling tool 30 using multiple iterations of the example method 400 of Figure 8B. With each successive target point along the desired path of the second wellbore 40, the achieved path of the second wellbore 40 gets closer to the desired path.

[0085] In certain embodiments, the second wellbore path may be a predetermined distance (e.g., 30 – 50 meters separation) from the first wellbore path that is sufficiently large such that magnetic ranging is not conducted. In certain such embodiments (e.g., when so-called in-fill drilling is carried out), the steering signals can be based on information regarding the absolute spatial position of the first wellbore 10 and the second wellbore 40. The first wellbore path may be provided by surveys conducted earlier while the second wellbore path may be determined using an on-board survey system (e.g., a magnetic survey system, a gyro survey system, or a combination of a magnetic and a gyro survey system) of the drilling tool 30 within the second wellbore 40. For example, a gyro survey system can be used to provide information regarding the second wellbore path, and information from magnetic sensors can be used to supplement the gyro-derived information (e.g., for quality assurance of changes in the gyro-derived information). In certain embodiments, the distance between the second wellbore 40 and the first wellbore path is too large for magnetic ranging to be used, while in certain other embodiments, magnetic ranging measurements are used to supplement the absolute spatial position measurements.

[0086] For example, the inclination of the drilling tool 30 may be determined using measurements of the gravitational vector obtained from a plurality (e.g., a triad) of

accelerometers of the drilling tool 30, the accelerometers mounted to have their sensitive axes nominally coincident with the xyz axes of the drilling tool 30. The tool azimuth may be determined using a combination of the gravitational measurements and measurements of the Earth's rotation vector obtained from a plurality (e.g., a triad) of rate gyroscopes, also mounted with their sensitive axes nominally coincident with the xyz axes of the drilling tool 30. Steering signals (e.g., commands) can then be generated (e.g., by the computer system) and transmitted to the steering mechanism, with the steering signals being functions of the inclination and azimuth differences between the target direction and tool orientation so as to cause the drilling tool 30 to rotate to point in the direction of the next target location as drilling proceeds.

[0087] To define accurately the target vector in the chosen reference frame, accurate information regarding the drilling tool position is desirable. Such accurate drilling tool position information can be generated by combining the measured inclination and azimuth with the distance moved along the path of the second wellbore 40 (e.g., the measured depth of the second wellbore 40). For example, such information can be generated using a minimum curvature process. Other methods for determining the depth of the second wellbore 40 can be based entirely on downhole measurements (rather than surface measurements), examples of which are described in U.S. Patent Nos. 6,957,580 and 8,065,085.

[0088] In general, the path of the first wellbore 10 will not be straight. Therefore, the absolute location of the target box 50 will move as the second wellbore 40 is drilled in order to maintain a fixed relative position with respect to the first wellbore 10. A strategy is therefore desirable for moving from one target box location to the next as the second wellbore 40 is drilled. One possible strategy is to select a new target box 50 as the second wellbore 40 approaches the previous target box 50. The frequency of the target boxes along the desired wellbore path, along with the dog-leg capability of the rotary steerable tool, can be selected to ensure that the distance of the second wellbore 40 from the first wellbore 10 is maintained to within acceptable limits.

Examples of Gyro-Assisted Magnetic Ranging

[0089] In certain embodiments, the techniques described herein can utilize combinations of static gyro surveying, static magnetic surveying, magnetic ranging

surveying, and dynamic magnetic analysis during drilling at various phases of the drilling process. In the example case of steam assisted gravity drainage (SAGD) drilling, the ends 12, 42 at or near the Earth's surface of the first wellbore 10 (e.g., the previously-drilled target wellbore) and the second wellbore 40 (e.g., the wellbore being drilled), respectively, are spaced substantially apart from one another, as schematically illustrated in Figure 11. Figure 11 includes a plan view of the first and second wellbores 10, 40 from above the Earth's surface in a direction perpendicular to the Earth's surface, and a section view in a direction parallel to the Earth's surface. In certain such configurations, there is little or no magnetic interference from the casings of the first wellbore 10 to be detected by the at least one sensor module 20 of the drilling tool 30 in the second wellbore 40 being drilled. In certain such configurations, standard gyro surveying can be performed during the initial phase of the drilling process to determine the position of the second wellbore 40, while monitoring data generated by the at least one sensor module 20 (e.g., by at least one longitudinal axis magnetometer) to detect the approach to the first wellbore 10 (e.g., the approach to the casings of the first wellbore 10 and/or the electromagnet 60 within the first wellbore 10).

[0090] In certain embodiments, the electromagnet 60 can be positioned at or near the planned interception point 70 of the two wellbores (e.g., at the point at which the second wellbore 40 is first at the desired distance for "twinning" the first wellbore 10). In certain embodiments, the electromagnet 60 can be switched on (e.g., for a single shot of about 40 seconds) and positioned at a distance (e.g., between about 10 meters and about 60 meters; about 40 meters) before the interception point 70 and the measurements by the axial magnetometer of the at least one sensor module 20 can be monitored for the switch point, as described below. Due to the possibility of any accumulative or gross errors having been part of each well survey, the spatial positions may be incorrect. To compensate for the possibility of any such spatial positional errors, it can be advantageous to start the magnetic ranging process sufficiently ahead of the perceived interception point 70. In certain embodiments, the electromagnet 60 is positioned at a distance before the interception point 70 that advantageously allows safe drilling of the second wellbore 40 to within a predetermined distance from the first wellbore 10 at which magnetic ranging can be initiated and then used (e.g., to follow a second wellbore path that is parallel to the first wellbore path).

[0091] As the second wellbore 40 approaches the electromagnet 60 in the first wellbore 10, the measured magnetic field 62 from the electromagnet 60 will increase and the flux angle will change. The measurements of the magnetic field can be used to derive (e.g., converted into) information regarding the position of the at least one sensor module 20 relative to the electromagnet 60. In certain embodiments, this derivation uses a predetermined mapping of the parameters of the magnetic field generated by the electromagnet 60 (e.g., the three orthogonal components of the magnetic field; the axial field component and the cross axial field component; the magnitude and the flux angle) as a function of position relative to the electromagnet 60. This mapping can be stored in memory of the computer system controlling the drilling of the second wellbore 40 (e.g., can be stored in the form of a model, simulation, database, lookup table, or other format). For example, a finite element calculation package (e.g., David Meeker, "Finite Element Method Magnetics," Version 4.2, User's Manual, 2010) can be used to derive the mapping of expected magnetic parameter values for two-dimensional planar or axisymmetric configurations. The mapping can have sufficient resolution to provide the desired level of precision in position as a function of measured magnetic field 62. In certain embodiments, interpolation among the values in the mapping can be used to find the appropriate position corresponding to the measured magnetic field parameter values.

[0092] In certain embodiments, as described more fully below, the measured axial field component (M_z) of the magnetic field along the longitudinal axis of the second wellbore 40 may advantageously be compared to the predetermined mapping of the magnetic field so as to be used to determine the position of the at least one sensor module 20 relative to the electromagnet 60. The measured axial field component can be measured in this manner during drilling of the second wellbore 40 (e.g., while the at least one sensor module 20 is rotating about the longitudinal axis) or during periods when drilling using the drill string 30 has stopped (e.g., while the at least one sensor module 20 is not rotating about the longitudinal axis). Use of the measured axial field component is possible during drilling since the values of the axial field component measured by the rotating sensor module 20 remain unchanged during the drilling-related rotation of the at least one sensor module 20 about its longitudinal axis. In other words, the measured axial field component is not

dependent on the rotation of the at least one sensor module 20 about its longitudinal axis. In addition, while the measured cross axial field components (M_x and M_y) do vary while the at least one sensor module 20 rotates about its longitudinal axis, the measured flux angle relative to the longitudinal axis of the at least one sensor module 20 (e.g., $\text{atan}[(M_x^2 + M_y^2)^{1/2}/M_z]$) does not; it is dependent on the spatial position of the at least one sensor module 20 relative to the electromagnet 60.

[0093] In certain embodiments, during periods in which drilling using the drill string 30 has stopped, the measured cross axial field components (M_x and M_y) may be used in addition to the measured axial field component (M_z), as described more fully below. In certain such embodiments, the measured flux angle relative to the longitudinal axis of the at least one sensor module 20 can be calculated from the axial and cross axial field components (e.g., $\text{atan}[(M_x^2 + M_y^2)^{1/2}/M_z]$), without using accelerometer measurements (e.g., from the at least one sensor module 20). In certain other embodiments, such accelerometer measurements may be used in conjunction with the measured axial and cross axial field components (e.g., to determine the orientation relative to the Earth's gravity). In certain embodiments, the spatial position of the at least one sensor module 20 in the second wellbore 40 relative to the electromagnet 60 in the first wellbore 10 can be determined by deriving the flux angle using the orientation of the at least one sensor module 20 (e.g., using accelerometer data), the angle of interception of the longitudinal axis of the at least one sensor module 20, the cross axial tool face interception (e.g., using accelerometer data), and the orientation of the electromagnet 60 (e.g., from historical data). Other methods may also be used to derive the target well flux angle interception. In certain embodiments, the relative position of the second wellbore 40 to the first wellbore 10 can be derived (e.g., while steering the drilling tool 30 with a rotary steerable assembly or a three-dimensional steerable device).

[0094] Figure 12A schematically illustrate the magnetic field 62 generated by an electromagnet 60 in accordance with certain embodiments described herein. The left side of Figure 12A schematically illustrates a side view of the first wellbore 10, the electromagnet 60, and the magnetic field 62, showing that the magnetic field 62 is cross axial to the first wellbore 10 (e.g., with an axial field component parallel to the longitudinal axis of zero) at various positions spaced from the first wellbore 10 and along the first wellbore 10 (e.g., as denoted by the dashed lines). As described more fully below, these positions can be

considered to be “switch points.” The right side of Figure 12A schematically illustrates a view of the first wellbore 10, the electromagnet 60, and the magnetic field 62, which also shows that the cross axial component of the magnetic field 62 at these switch points are directed either towards or away from the first wellbore 10. While an increase or decrease of the current running through the electromagnet 60 results in a respective increase or decrease of the magnetic field intensity, the flux line shape of the magnetic field remains unchanged by such changes of the current. Therefore, a set of predetermined values of the parameters that characterize the magnetic field generated by the electromagnet can be obtained (e.g., by measuring these values for at least one current running through the electromagnet 60 prior to the electromagnet 60 being inserted into the first wellbore 10). The set of predetermined values of the parameters that characterize the magnetic field can then be used in comparison with values measured while the electromagnet 60 is within the first wellbore 10 (once the predetermined values are scaled to the same current running through the electromagnet 60 during the measurements using the at least one sensor module 20 in the second wellbore 40) in accordance with certain embodiments described herein.

[0095] The top portion of Figure 12B schematically illustrates an SAGD configuration in which a portion of the second wellbore 40 (e.g., the drilling well) is in proximity to and parallel to a portion of the first wellbore 10 (e.g., the target well) containing the electromagnet 60. The bottom portion of Figure 12B schematically illustrates measured values of the axial field component (in arbitrary units) measured by a longitudinal axis magnetometer at various positions along the second wellbore 40. As the longitudinal axis magnetometer of the at least one sensor module 20 moves along the second wellbore 40, approaching the electromagnet 60 in the first wellbore 10, and traversing past the electromagnet 60 (e.g., moving from left to right in Figure 12B), the flux angle detected by the longitudinal axis magnetometer will switch direction and the axial field component detected by the longitudinal axis magnetometer will vary. A first switch point (denoted in Figure 12B by a first star) can be defined as the position of the longitudinal axis magnetometer where the component of the magnetic flux parallel to the second wellbore 40 (e.g., the axial field component) switches from pointing in one direction to pointing in the opposite direction (e.g., changes sign from having a negative value to having a positive value). A second switch point (denoted in Figure 12B by a second star) can be defined as the

position of the longitudinal axis magnetometer where the component of the magnetic flux parallel to the second wellbore 40 (e.g., the axial field component) switches back to pointing in the direction it pointed prior to reaching the first switch point (e.g., switches sign from having a positive value to having a negative value). At each switch point, the intensity of the detected magnetic field 62 can be used to derive the total distance and cross axial distance to the pole of the electromagnet 60. For example, by comparing the measured magnetic field parameters to a set of predetermined values of these parameters that characterize the magnetic field generated by the electromagnet 60 (e.g., in a table, database, model, simulation, or other form), certain embodiments described herein can derive (e.g., convert; translate) the measurements of the magnetic field to values of the total distance and cross axial distance from the at least one sensor module 20 to the pole of the electromagnet 60.

[0096] At the first switch point, a magnetic ranging survey can be taken to determine the relative position of the second wellbore 40 with respect to the first wellbore 10. In certain embodiments, a second magnetic ranging survey may be taken at the second switch point if deemed necessary. For example, if the first magnetic ranging survey is deemed to have a sufficiently reduced quality (e.g., noisy; large jumps in values between adjacent points), then the second magnetic ranging survey may be taken. One or both of the switch points can be optimal positions at which to take a magnetic ranging survey as the cross axial component of the magnetic flux is large at the switch points, which can help define more accurately the relative position of the second wellbore 40 to the first wellbore 10.

[0097] Upon determining the relative position of the second wellbore 40 to the first wellbore 10, action can be taken to steer the second wellbore 40 within the target box 50. Once the relative position of the second wellbore 40 is determined with respect to the target box 50, the electromagnet 60 can be moved to a new position further down the first wellbore 10 (e.g., 96 meters further down the first wellbore 10) and gyro survey measurements can be resumed at each survey station (e.g., at positions spaced from one another by 11-13 meters). As the second wellbore 40 again approaches the electromagnet 60, the above-described procedure can be repeated.

[0098] The magnetic field 62 from the first wellbore 10 (e.g., the electromagnet 60) should be detectable many tens of meters before the second wellbore 40 is parallel to the first wellbore 10. Although optimal positions for the magnetic ranging survey has been

described above at the first and second switch points, it is not essential that a magnetic ranging survey is taken at one or both of these positions. In certain embodiments, a magnetic ranging survey can be carried out at any position along the second wellbore 40 where the magnetic field 62 from the first wellbore 10 is detectable.

[0099] In certain embodiments, the procedure described herein can be used for horizontal to vertical interceptions, or for high angle interceptions (e.g., for Coal Bed Methane drilling, synthetic gas drilling, and many other applications). For example, as schematically illustrated by the top left portion and the right portion of Figure 12C, a second wellbore 40 can extend in a direction that is not generally parallel to the first wellbore 10 (e.g., that crosses above or below the first wellbore 10). As shown in the bottom left portion of Figure 12C, as the longitudinal axis magnetometer of the at least one sensor module 20 moves along the second wellbore 40, approaching the electromagnet 60 in the first wellbore 10, and traversing past the electromagnet 60 (e.g., moving from left to right in the top left portion of Figure 12C), the measured axial field component (shown in arbitrary units in the bottom left portion of Figure 12C) detected by the longitudinal axis magnetometer will switch direction at the point of closest approach of the second wellbore 40 to the first wellbore 10 (e.g., the switch pattern in the high angle interceptions occurs at the point of closest approach of the second wellbore 40 to the first wellbore 10).

[0100] In certain embodiments, the rate of change of the intensity of the magnetic field, the flux angle, and the flux direction may be used to determine the distances between the second wellbore 40 and the first wellbore 10 and the relative cross axial position. For example, as the pole of the electromagnet 60 is approached, the detected rate of change increases, and this information can be used to dynamically monitor the approach of the drilling tool 30 to the first wellbore 10.

[0101] Figure 13A schematically illustrates an example configuration including a table of example measured values of the various parameters of the magnetic field 62 from the electromagnet 60 in accordance with certain embodiments described herein. These measured values can be determined by the at least one sensor module 20 (e.g., a longitudinal axis magnetometer) within the second wellbore 40, and can be used in conjunction with a set of predetermined correlation of these parameters (e.g., magnetic field intensities; magnetic field components; flux angle; gradients of these parameters) with the distance between the at least

one sensor module 20 and the electromagnet 60 to derive the position of the at least one sensor module 20 to the electromagnet 60. Besides the magnetic flux lines of the magnetic field 62, Figure 13A includes dashed lines which denote lines of constant total magnetic intensity. The values shown in Figure 13A are representative of values after contributions from the Earth's magnetic field have been removed.

[0102] For example, a longitudinal axis magnetometer within the second wellbore 40 at a first position relative to the electromagnet 60 in the first wellbore 10 can measure the values of (measured total magnetic field intensity; the axial magnetic field component; flux angle) to be (300 nT; -260 nT; 300 degrees). Using the set of predetermined correlations of these parameters with position, these measurements can be used to derive a relative distance of 5.5 meters between the long axis magnetometer and the electromagnet 60. Depending on the trajectory taken by the second wellbore 40, a second set of measurements taken by the long axis magnetometer at a second position can have different values of the measured parameters. For example, a second set of measurements taken by the long axis magnetometer at a second position can measure the values to be (300 nT; +254 nT; 58 degrees). Again using the predetermined correlation of these parameters with position, the second position can be determined to be at the location labeled "1" in Figure 13A which is a relative distance of 6.7 meters from the electromagnet 60. If instead the second position is at either the location labeled "2" or "3" in Figure 13A, the measured values will be different and so will the relative distance to the electromagnet 60.

[0103] The gradients of one or more of the parameters of the magnetic field can be used to determine the relative distance between the at least one sensor module 20 and the electromagnet. In certain embodiments, the relative distance at the second position (e.g., at one of the locations labeled "1", "2", or "3" as shown in Figure 13A) can be determined using only the gradient of the axial magnetic field component from the first position to the second position. In certain other embodiments, the gradient of the flux angle may also be used.

[0104] In certain embodiments, these gradients are determined using measurements taken while drilling (e.g., when the at least one sensor module 20 is rotating) or while the drill string 30 is stationary (e.g., the at least one sensor module 20 is not rotating). As described above, if the at least one sensor module 20 is rotating, the long axis

magnetometer can still provide useful measurements (e.g., to determine the gradient), while the variations (e.g., noise) of measurements from the cross axial magnetometers may not. The gradient values are dependent on the angle of orientation and the relative spatial position between the at least one sensor module 20 and the electromagnet 60. The derivation of the relative distance during drilling can be useful in determining whether the second wellbore 40 is approaching the first wellbore 10, paralleling the first wellbore 10, or deviating away from the first wellbore 10.

[0105] However, while the relative distance may be derived from the magnetic field measurements, because the magnetic field is radially symmetric around the electromagnet 60, additional information may be used to make a determination of the angular position of the at least one sensor module 20 with respect to the electromagnet 60. For example, the orientation (e.g., inclination and azimuth) of both the at least one sensor module 20 and the electromagnet 60 can be known from static and historical surveys, and using such information, the spatial position of the second wellbore 40 relative to the first wellbore 10 can be derived. In certain embodiments, measurements taken while the at least one sensor module 20 is not rotating (e.g., stationary) can be used to determine which cross axial quadrant the at least one sensor module 20 is in with respect to the electromagnet 60. Once this additional information is obtained, the second wellbore 40 can then be steered correctly during drilling to its optimum position using only the axial magnetic field component measurements, thereby providing the ability to dynamically monitor the approach of the second wellbore 40 to the first wellbore 10.

[0106] Figure 13B schematically illustrates an example well paralleling configuration including a table of example measured values of the various parameters of the magnetic field 62 from the electromagnet 60 in accordance with certain embodiments described herein. Besides the magnetic flux lines of the magnetic field 62, the bottom right portion of Figure 13B is a section view that includes dashed lines which denote lines of constant total magnetic intensity. The bottom left portion of Figure 13B shows a cross-sectional view of the cross-axial magnetic flux pattern in a plane generally perpendicular to the first wellbore 10 and to the second wellbore 40 (denoted by a star). The values shown in Figure 13B are representative of values after contributions from the Earth's magnetic field have been removed.

[0107] For example, at a series of positions labeled “A” through “F” in Figure 13B, a longitudinal axis magnetometer within the second wellbore 40 can measure the various magnetic field values. The values of the axial magnetic field component in the table of Figure 13B can be measured dynamically (e.g., during drilling) while the values of the total magnetic field intensity, flux angle, and cross axial magnetic field components can be measured statically (e.g., while the drill string 30 is stationary). Using the set of predetermined correlations of these parameters with position, these measurements can be used to derive the relative distance between the second wellbore 40 and the first wellbore 10 and the angle of orientation of the second wellbore 40 about the first wellbore 10. As shown in Figure 13B, using the set of predetermined correlations of the measured magnetic field parameters with position, the relative distance between the second wellbore 40 and the first wellbore 10 is determined to be substantially constant (e.g., 5.5 – 5.9 meters) along the length of the second wellbore 40 from position “A” to position “F”, and the angle of orientation of the second wellbore 40 is also determined to be substantially constant (e.g., 310 degrees) as well, indicative of successful paralleling of the second wellbore 40 to the first wellbore 10.

[0108] Figure 13C schematically illustrates an example horizontal to vertical interception configuration including a table of example measured values of the various parameters of the magnetic field 62 from the electromagnet 60 in accordance with certain embodiments described herein. As shown in the section view in the left bottom portion of Figure 13C and the side view in the middle bottom portion of Figure 13C, the second wellbore 40 extends downward in a generally vertical direction generally towards the first wellbore 10 containing the electromagnet 60. At a series of positions labeled “J” through “O” in Figure 13C, a longitudinal axis magnetometer within the second wellbore 40 can measure the various magnetic field values. The values of the axial magnetic field component in the table of Figure 13C can be measured dynamically (e.g., during drilling) while the values of the total magnetic field intensity, flux angle, and cross axial magnetic field components can be measured statically (e.g., while the drill string 30 is stationary). Using the set of predetermined correlations of these parameters with position, these measurements can be used to derive the relative distance between the second wellbore 40 and the first wellbore 10 and the angle of orientation of the second wellbore 40 about the first wellbore 10.

[0109] As shown in Figure 13C, using the set of predetermined correlations of the measured magnetic field parameters with position, the region of the second wellbore 40 in closest approach to the first wellbore 10 (e.g., between points labeled “M” and “N” in Figure 13C) has a relative distance between the second wellbore 40 and the first wellbore 10 between 7.8 meters and 8.1 meters. At these two positions (e.g., where the measurements taken during drilling) indicate the closest approach, additional measurements can be taken while the drill string 30 is stopped to measure the cross axial field components to get further information regarding the relative position of the second wellbore 40 to the first wellbore 10. While Figure 13C shows example values for a second wellbore 40 that passes by the first wellbore 10, similar information can be used to steer the second wellbore 40 to intersect the first wellbore 10 while drilling commences. In certain embodiments in which previously-obtained measurements of the magnetic field parameters with position are not available (e.g., for certain passive ranging situations), the shape of the magnetic field can be derived (e.g., determined) from symmetry-based assumptions (e.g., symmetry about the longitudinal axis of the wellbore casing) and using triangulation to provide a set of predetermined correlations of the measured magnetic field parameters with position.

[0110] In certain embodiments, upon completion of drilling the second wellbore 40, the gyro of the at least one sensor module 20 may be used in continuous mode, static mode, or in a combination of the two modes, while the at least one sensor module 20 is pulled out of the second wellbore 40. In certain such embodiments, these measurements may be used in conjunction with the gyro survey data gathered while drilling the second wellbore 40 to generate a definitive wellbore position or trajectory.

[0111] In certain embodiments, the current flowing through the electromagnet 60 can be switched from one direction to the opposite direction, thereby switching the directions of the magnetic flux lines of the resulting magnetic field 62. By taking ranging measurements while the current is flowing in one direction and then the other, certain embodiments described herein are able to remove the effect of the Earth’s magnetic field from the measurements. In certain embodiments, the components of the magnetic field sensed by the at least one magnetometer module when current is flowing in a first direction in the coils of the electromagnet, denoted by the subscript 1, (H_{xr1} , H_{yr1} , H_{zr1}) can be

expressed as the sum of the components of the Earth's magnetic field (H_x , H_y , H_z) and the components of the interference field (H_{xi} , H_{yi} , H_{zi}) as follows:

$$\begin{aligned} H_{xr1} &= H_x + H_{xi} \\ H_{yr1} &= H_y + H_{yi} \\ H_{zr1} &= H_z + H_{zi} \end{aligned}$$

[0112] If the current in the electromagnet is reversed, the direction of the measured interference field is reversed, and components of the magnetic field sensed by the at least one magnetometer module, denoted by the subscript 2, (H_{xr2} , H_{yr2} , H_{zr2}) can be expressed as follows:

$$\begin{aligned} H_{xr2} &= H_x - H_{xi} \\ H_{yr2} &= H_y - H_{yi} \\ H_{zr2} &= H_z - H_{zi} \end{aligned}$$

The interference field can now be determined by subtracting the second set of readings from the first set of readings and dividing the result by two, viz.

$$\begin{aligned} H_{xi} &= (H_{xr1} - H_{xr2})/2 \\ H_{yi} &= (H_{yr1} - H_{yr2})/2 \\ H_{zi} &= (H_{zr1} - H_{zr2})/2 \end{aligned}$$

[0113] These readings can then be used to compute the range and direction to the target well as described above.

[0114] In certain other embodiments, a single magnetic ranging survey is taken at each desired position without switching the current of the electromagnet 60, and the Earth's magnetic field is removed by using the gyro measurements of the azimuth, inclination, and rotation angles, and using the magnetic dip and total magnetic field from measurements at the rig site or derived from models (e.g., BGGM, HDGM, etc.)(e.g., as described above, using explicit knowledge regarding the components of the Earth's magnetic field, such as the azimuth component). By taking only a single survey, certain such embodiments can advantageously save time. In certain other embodiments, two measurements with the reversal of the current direction in the electromagnet coils, Earth's field, and knowledge of the azimuth may not be used.

[0115] Figure 14 is a flow diagram of an example method 500 for gyro-assisted magnetic ranging in the context of SAGD drilling using a rotary steerable drilling tool 30 in accordance with certain embodiments described herein. In an operational block 510, the

method 500 comprises steering the drilling tool 30 to a position at which a magnetic field 62 from an electromagnet 60 in the first wellbore 10 (e.g., the target wellbore) can be detected by at least one sensor module 20 of the drilling tool 30. For example, the electromagnet 60 (e.g., solenoid) can be positioned within the first wellbore 10 at a location at which the second wellbore 40 is to begin “twinning” to the first wellbore 10, and the drilling tool 30 can be steered to a position sufficiently close to the electromagnet 60 such that the at least one sensor module 20 detects the magnetic field 62.

[0116] In an operational block 520, the method 500 further comprises performing a multi-station analysis to detect BHA biases. In certain embodiments, performing the multi-station analysis in the operational block 520 can occur while steering the drilling tool 30 to the position in the operational block 510. The detected BHA biases can be used subsequently in the method 500 as described more fully below.

[0117] In an operational block 530, the method 500 further comprises monitoring measurements from a longitudinal axis magnetometer of the at least one sensor module 20 as the drill path of the second wellbore 40 approaches the electromagnet 60 in the first wellbore 10. For example, the electromagnet 60 may be activated once, twice, or more, and can be activated for a predetermined period of time (e.g., 40 seconds). In certain embodiments, monitoring the measurements from the longitudinal axis magnetometer comprises determining an angle of interception (e.g., a slant range) and a direction of the at least one sensor module 20 with respect to the electromagnet 60. In certain such embodiments, determining the angle of interception and the direction comprises using the detected BHA biases to correct the measurements from the longitudinal axis magnetometer (e.g., to remove the BHA biases) and using knowledge of the Earth’s field (e.g., in conjunction with gyroscopic measurements of azimuth of the at least one sensor module 20) to correct the measurements from the longitudinal axis magnetometer (e.g., to remove the contributions from the Earth’s magnetic field).

[0118] In an operational block 540, the method 500 further comprises making stationary magnetic ranging survey measurements using the at least one sensor module 20. Making the measurements can comprise halting drilling of the second wellbore 40 upon the at least one sensor module 20 reaching a predetermined location with respect to the electromagnet 60. For example, the drilling of the second wellbore 40 can be halted upon the

at least one sensor module 20 reaching the first switch point, as discussed herein, and then the stationary magnetic ranging survey measurements can be made while the at least one sensor module 20 is at the first switch point. In certain embodiments, making the stationary magnetic ranging survey measurements comprises using the detected BHA biases and the knowledge of the Earth's magnetic field at the azimuth of the at least one sensor module 20 to correct the stationary magnetic ranging survey measurements.

[0119] In an operational block 550, the method 500 further comprises moving the electromagnet 60 to a different position within the first wellbore 10. For example, the electromagnet 60 can be advanced to a position a predetermined distance (e.g., 96 meters) further down the first wellbore 10.

[0120] In an operational block 560, the method 500 further comprises making magnetic ranging measurements and further drilling the second wellbore 40 in a trajectory that is substantially parallel to the first wellbore 10. In certain embodiments, the magnetic ranging measurements are used to compute drilling commands to be performed by the drilling tool 30 to advance a predetermined distance (e.g., sufficient for the creation of the next wellbore section; an example of which includes 11-13 meters) in the trajectory substantially parallel to the first wellbore 10.

[0121] In an operational block 570, the method 500 further comprises making stationary gyro survey measurements using the at least one sensor module 20 and using the stationary gyro survey measurements in determining a separation and angle of approach of the at least one sensor module 20 to the first wellbore 10. Making the measurements can comprise halting drilling of the second wellbore 40 upon reaching the predetermined distance.

[0122] In an operational block 580, the method 500 further comprises using the stationary gyro survey measurements to compute drilling commands to be performed by the drilling tool 30 to advance a predetermined distance (e.g., sufficient for the creation of the next wellbore section; an example of which includes 11-13 meters) and continuing the drilling of the second wellbore 40.

[0123] The method 500 can further comprise iterating the operational blocks 560-580 (denoted in Figure 14 by the arrow 590) until the magnetic field 62 from the electromagnet 60 is again detected. The method 500 can further comprise iterating the

operational blocks 530-580 (denoted in Figure 14 by the arrow 592) for drilling subsequent sections (e.g., 96 meters) of the second wellbore 40.

[0124] Conditional language used herein, such as, among others, "can," "could," "might," "may," "e.g.," and the like, unless specifically stated otherwise, or otherwise understood within the context as used, is generally intended to convey that certain embodiments include, while other embodiments do not include, certain features, elements and/or states. Thus, such conditional language is not generally intended to imply that features, elements and/or states are in any way required for one or more embodiments or that one or more embodiments necessarily include logic for deciding, with or without author input or prompting, whether these features, elements and/or states are included or are to be performed in any particular embodiment.

[0125] Depending on the embodiment, certain acts, events, or functions of any of the methods described herein can be performed in a different sequence, can be added, merged, or left out completely (e.g., not all described acts or events are necessary for the practice of the method). Moreover, in certain embodiments, acts or events can be performed concurrently, e.g., through multi-threaded processing, interrupt processing, or multiple processors or processor cores, rather than sequentially.

[0126] The various illustrative logical blocks, modules, circuits, and algorithm steps described in connection with the embodiments disclosed herein can be implemented as electronic hardware, computer software, or combinations of both. To clearly illustrate this interchangeability of hardware and software, various illustrative components, blocks, modules, circuits, and steps have been described above generally in terms of their functionality. Whether such functionality is implemented as hardware or software depends upon the particular application and design constraints imposed on the overall system. The described functionality can be implemented in varying ways for each particular application, but such implementation decisions should not be interpreted as causing a departure from the scope of the disclosure.

[0127] The various illustrative logical blocks, modules, and circuits described in connection with the embodiments disclosed herein can be implemented or performed with a general purpose processor, a digital signal processor (DSP), an application specific integrated circuit (ASIC), a field programmable gate array (FPGA) or other programmable logic device,

discrete gate or transistor logic, discrete hardware components, or any combination thereof designed to perform the functions described herein. A general purpose processor can be a microprocessor, but in the alternative, the processor can be any conventional processor, controller, microcontroller, or state machine. A processor can also be implemented as a combination of computing devices, e.g., a combination of a DSP and a microprocessor, a plurality of microprocessors, one or more microprocessors in conjunction with a DSP core, or any other such configuration.

[0128] The blocks of the methods and algorithms described in connection with the embodiments disclosed herein can be embodied directly in hardware, in a software module executed by a processor, or in a combination of the two. A software module can reside in RAM memory, flash memory, ROM memory, EPROM memory, EEPROM memory, registers, a hard disk, a removable disk, a CD-ROM, or any other form of computer-readable storage medium known in the art. An exemplary tangible, computer-readable storage medium is coupled to a processor such that the processor can read information from, and write information to, the storage medium. In the alternative, the storage medium can be integral to the processor. The processor and the storage medium can reside in an ASIC. The ASIC can reside in a user terminal. In the alternative, the processor and the storage medium can reside as discrete components in a user terminal.

[0129] While the above detailed description has shown, described, and pointed out novel features as applied to various embodiments, it will be understood that various omissions, substitutions, and changes in the form and details of the devices or algorithms illustrated can be made without departing from the spirit of the disclosure. As will be recognized, certain embodiments described herein can be embodied within a form that does not provide all of the features and benefits set forth herein, as some features can be used or practiced separately from others. The scope of certain inventions disclosed herein is indicated by the appended claims rather than by the foregoing description. All changes which come within the meaning and range of equivalency of the claims are to be embraced within their scope.

WHAT IS CLAIMED IS:

1. A method to determine a distance, a direction, or both between an existing first wellbore and at least one sensor module of a drill string within a second wellbore being drilled, the method comprising:

using the at least one sensor module to measure a magnetic field and to generate at least one first signal indicative of the measured magnetic field;

using the at least one sensor module to gyroscopically measure an azimuth, an inclination, or both of the at least one sensor module and to generate at least one second signal indicative of the measured azimuth, inclination, or both; and

using the at least one first signal and the at least one second signal to calculate a distance between the existing first wellbore and the at least one sensor module, a direction between the existing first wellbore and the at least one sensor module, or both a distance and a direction between the existing first wellbore and the at least one sensor module.

2. The method of Claim 1, further comprising controlling the drill string using the calculated distance, the calculated direction, or both.

3. The method of Claim 2, wherein the drill string comprises a rotary steerable drilling tool.

4. The method of Claim 2, wherein controlling the drill string comprises generating at least one control signal in response to the calculated distance, the calculated direction, or both, and transmitting the at least one control signal to a steering mechanism of the drill string.

5. The method of Claim 1, wherein using the at least one sensor module to measure the magnetic field comprises using the at least one sensor module to measure an axial field component of the magnetic field along a longitudinal axis of the second wellbore.

6. The method of Claim 5, wherein the axial field component is measured during drilling of the second wellbore.

7. The method of Claim 1, further comprising:

using the azimuth, the inclination, or both with a model of the Earth's magnetic field to estimate a contribution from the Earth's magnetic field to the measured magnetic field;

subtracting the contribution from the measured magnetic field to calculate a corrected measured magnetic field; and

using the corrected measured magnetic field to calculate at least one of the distance and the direction between the existing first wellbore and the at least one sensor module.

8. A method for controlling a drill string spaced from an existing first wellbore, the drill string drilling a second wellbore, the method comprising:

receiving at least one first signal indicative of a magnetic field measured by at least a first sensor module of the drill string;

receiving at least one second signal indicative of an azimuth, an inclination, or both measured by at least a second sensor module of the drill string, the second sensor module comprising at least one gyroscopic sensor;

calculating a distance between the existing first wellbore and the first sensor module, a direction between the existing first wellbore and the first sensor module, or both a distance and a direction between the existing first wellbore and the first sensor module based on the at least one first signal and the at least one second signal; and

generating, in response to at least one of the calculated distance and the calculated direction, at least one control signal to be transmitted to a steering mechanism of the drill string.

9. The method of Claim 8, wherein the steering mechanism comprises a rotary steerable tool.

10. The method of Claim 8, further comprising transmitting the at least one control signal to a steering mechanism of the drill string.

11. The method of Claim 8, wherein the at least one first signal is indicative of a measured axial field component of the magnetic field along a longitudinal axis of the second wellbore.

12. The method of Claim 11, wherein the axial field component is measured during drilling of the second wellbore.

13. The method of Claim 8, further comprising:

using the azimuth, the inclination, or both with a model of the Earth's magnetic field to estimate a contribution from the Earth's magnetic field to the measured magnetic field;

subtracting the contribution from the measured magnetic field to calculate a corrected measured magnetic field; and

using the corrected measured magnetic field to calculate at least one of the distance and the direction between the existing first wellbore and the first sensor module.

14. A method for using a drilling tool to drill a second wellbore along a desired path substantially parallel to a first wellbore, the drilling tool comprising a steering mechanism, the method comprising:

(a) defining a first target position along a desired path of the second wellbore, the first target position spaced from a current position of the drilling tool by a first distance;

(b) performing magnetic ranging measurements and gyroscopic measurements of an azimuth, an inclination, or both of the drilling tool and using the magnetic ranging measurements and the gyroscopic measurements to determine a second distance between the current position of the drilling tool and the first wellbore;

(c) calculating a third distance between the first wellbore and the desired path of the second wellbore;

(d) calculating a target sightline angle with respect to the desired path of the second wellbore;

(e) measuring a tool path direction with respect to the first wellbore;

(f) calculating a steering angle;

(g) transmitting a steering signal to the steering mechanism to control the steering mechanism to adjust a tool path direction of the second wellbore by the steering angle; and

(h) actuating the steering mechanism to move the drilling tool to a revised current position.

15. The method of Claim 14, further comprising defining a second target position along the desired path of the second wellbore, the second target position spaced from the revised current position of the drilling tool by the first distance, and iterating steps (b)-(h).

16. The method of Claim 14, wherein the drilling tool comprises a first sensor module and a second sensor module, and the magnetic ranging measurements and the gyroscopic measurements are made using at least one of the first sensor module and the second sensor module.

17. The method of Claim 16, wherein the tool path direction is measured using at least one of the first sensor module and the second sensor module.

18. The method of Claim 14, wherein calculating the third distance, calculating the target sightline angle, and calculating the steering angle are performed by a computer processor.

19. A method for gyro-assisted magnetic ranging relative to a first wellbore using a rotary steerable drilling tool to drill a second wellbore, the method comprising:

(a) steering the drilling tool to a position at which a magnetic field from an electromagnet in the first wellbore can be detected by at least one sensor module of the drilling tool;

(b) performing a multi-station analysis to detect magnetic biases from the drilling tool;

(c) monitoring measurements from a longitudinal axis magnetometer of the at least one sensor module as a drill path of the second wellbore approaches the electromagnet in the first wellbore;

(d) making stationary magnetic ranging survey measurements using the at least one sensor module;

(e) moving the electromagnet to a different position within the first wellbore;

(f) making magnetic ranging measurements and further drilling the second wellbore in a trajectory that is substantially parallel to the first wellbore;

(g) making stationary gyro survey measurements using the at least one sensor module and using the stationary gyro survey measurements to determine a

separation and angle of approach of the at least one sensor module to the first wellbore;
and

(h) using the stationary gyro survey measurements to compute drilling commands to be performed by the drilling tool and continuing to drill the second wellbore.

20. The method of Claim 19, further comprising: (i) iterating steps (f)-(h) until the magnetic field from the electromagnet is again detected.

21. The method of Claim 20, further comprising: (j) iterating steps (c)-(h) for drilling subsequent sections of the second wellbore.

22. The method of Claim 19, wherein performing the multi-station analysis occurs concurrently with steering the drilling tool.

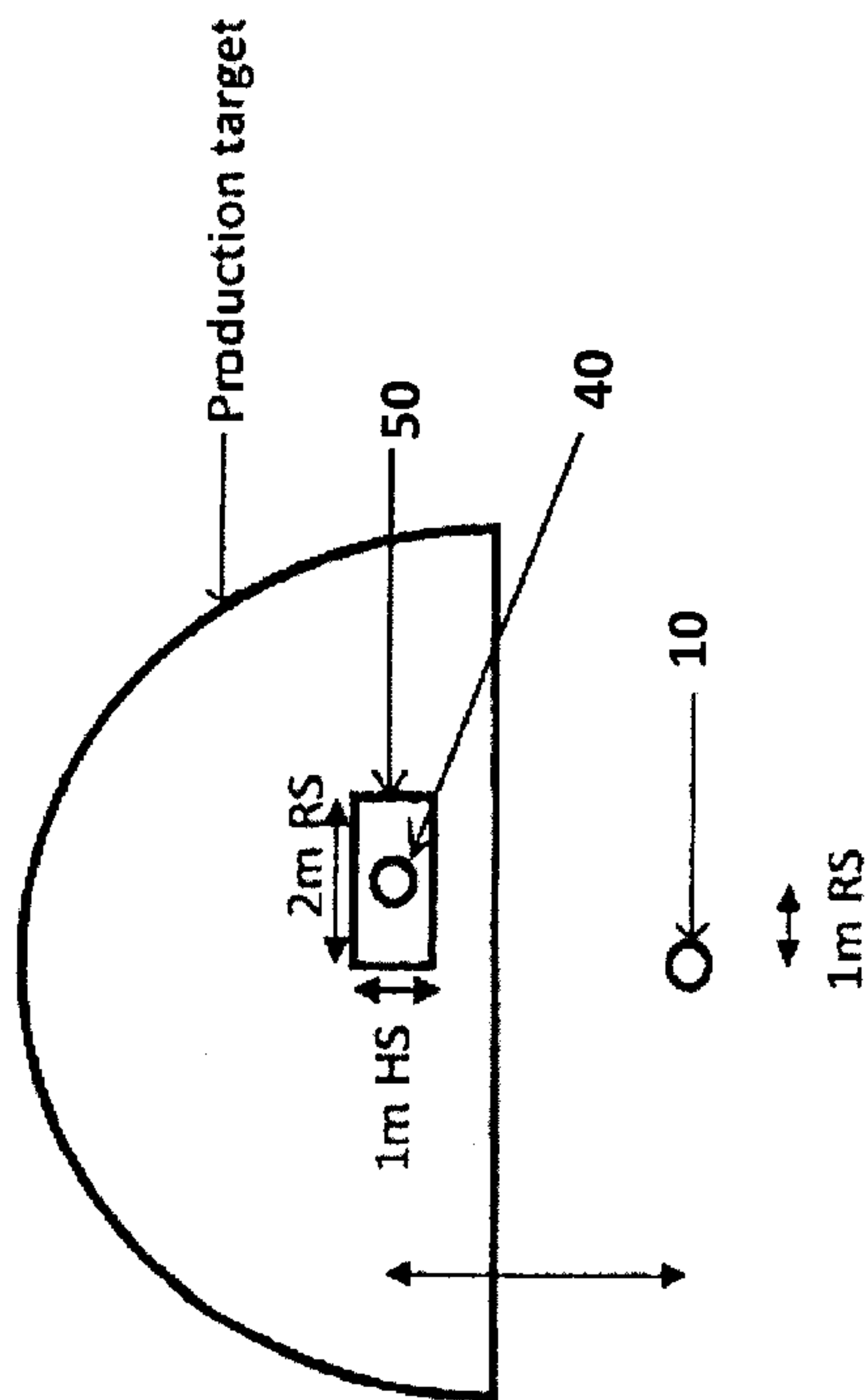
23. The method of Claim 19, wherein monitoring the measurements comprises determining a slant range and a direction of the at least one sensor module with respect to the electromagnet.

24. The method of Claim 23, wherein determining the slant range and the direction comprises using the detected magnetic biases.

25. The method of Claim 19, wherein making stationary magnetic ranging survey measurements comprises halting drilling of the second wellbore upon the at least one sensor module reaching a predetermined location with respect to the electromagnet.

26. The method of Claim 19, wherein making stationary magnetic ranging survey measurements comprises using the detected magnetic biases to correct the stationary magnetic ranging survey measurements.

Figure 1:



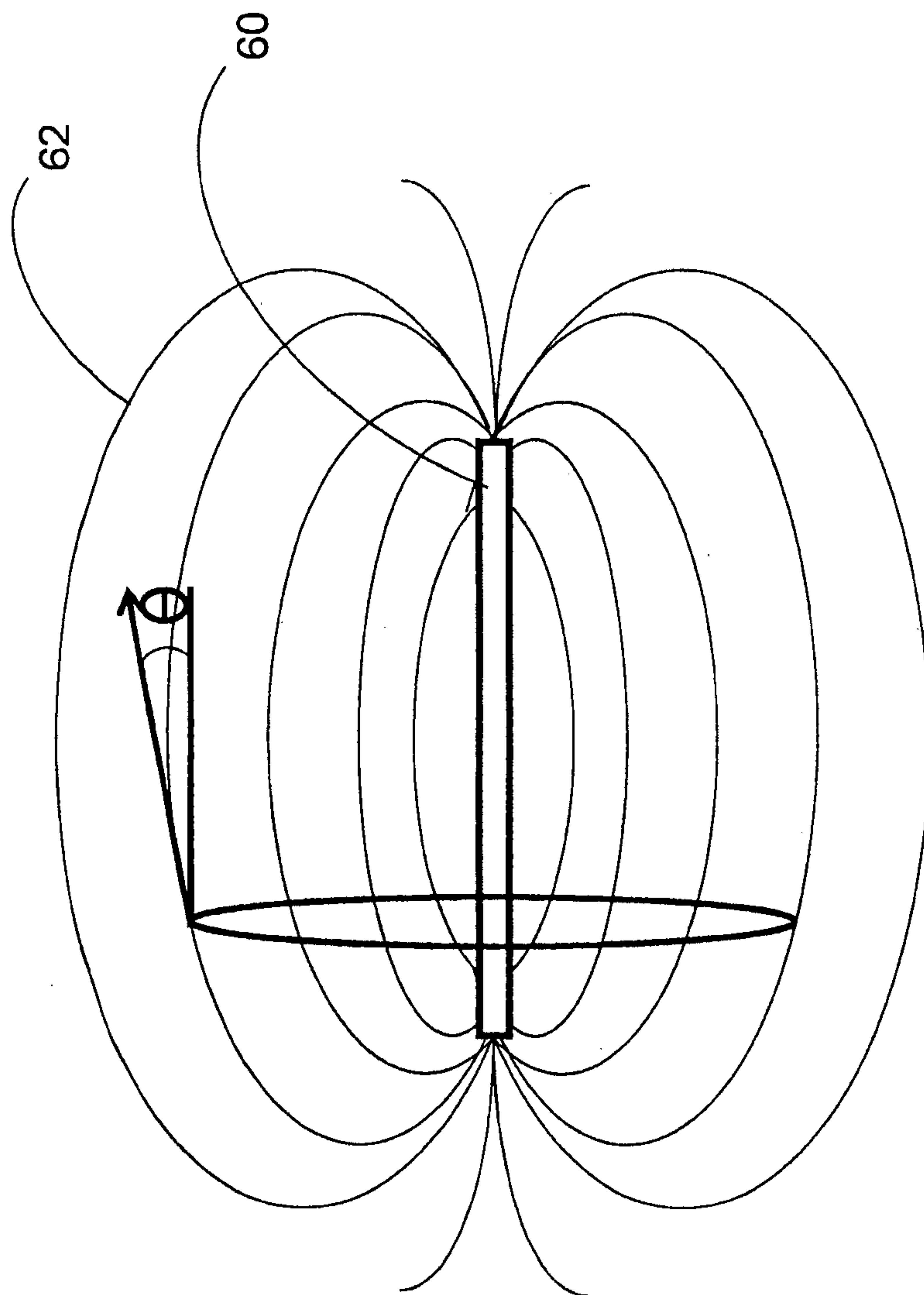
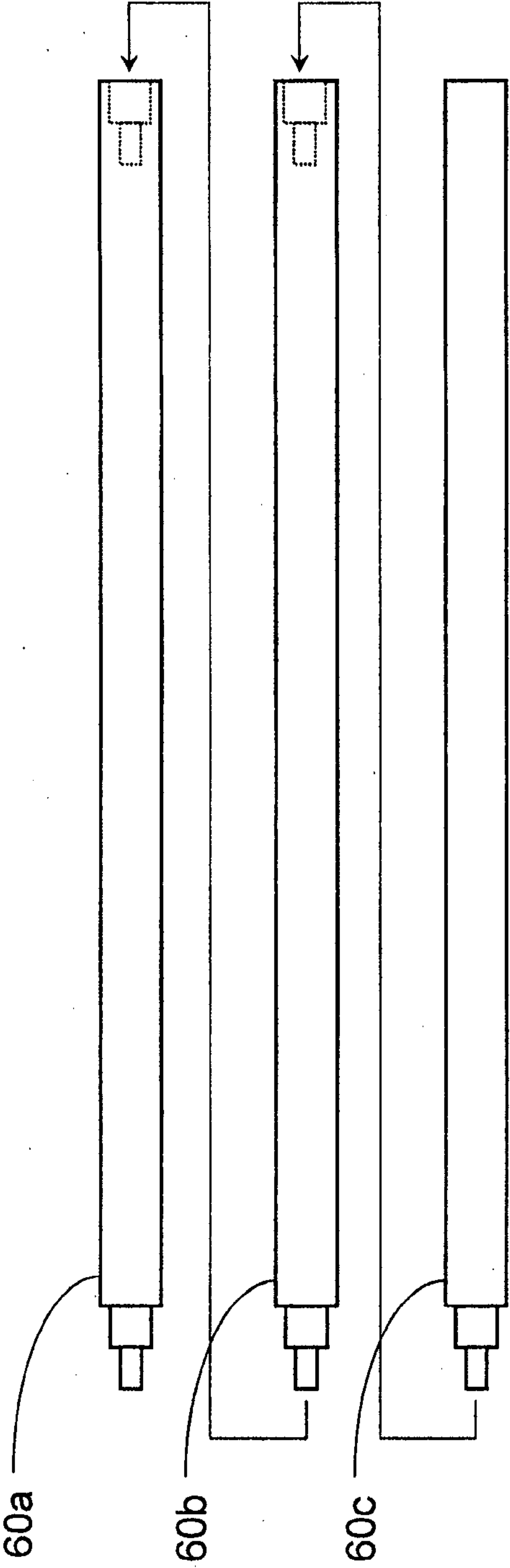


Figure 2A:

Figure 2B:



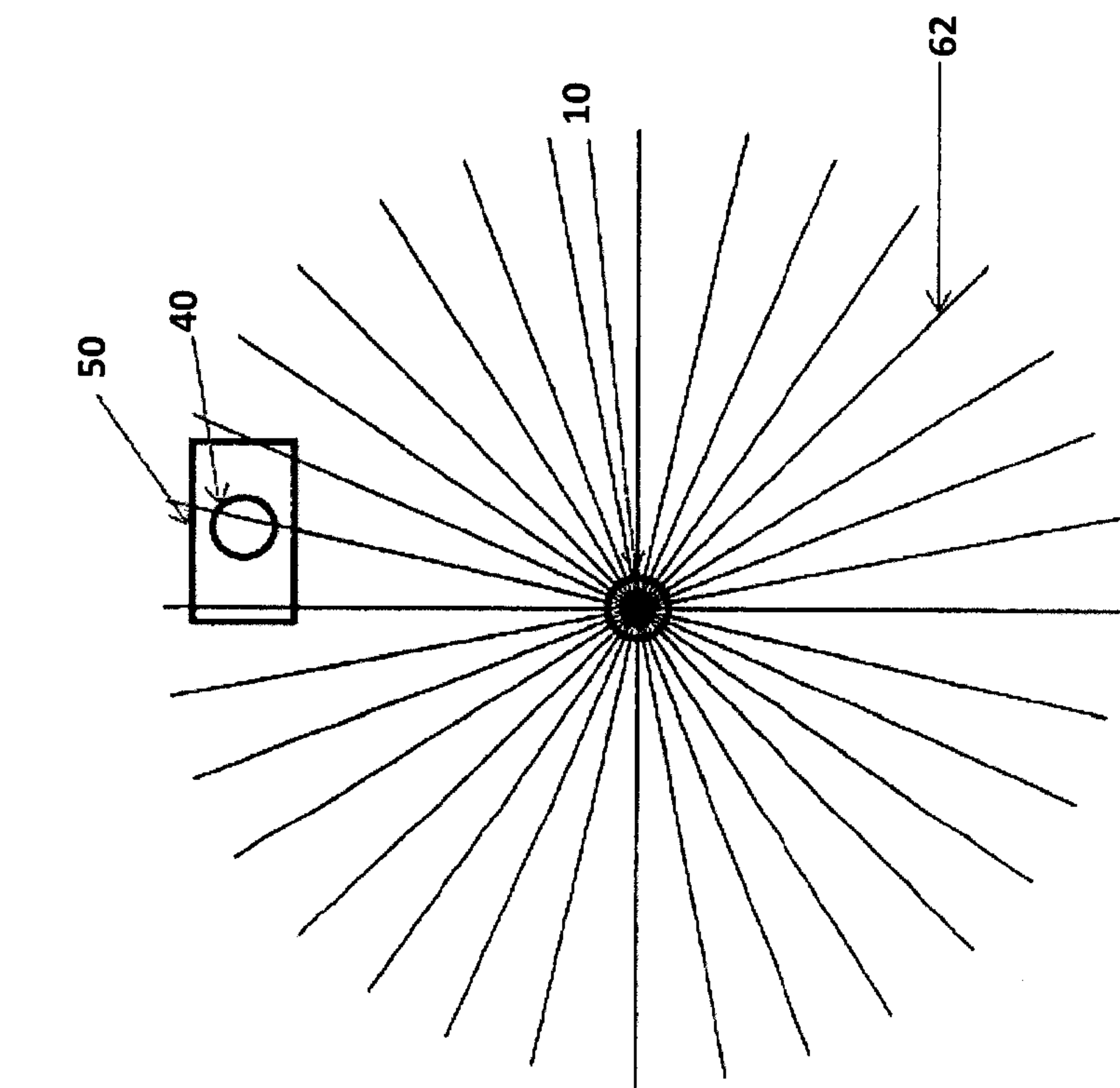


Figure 3A:

Figure 3B:

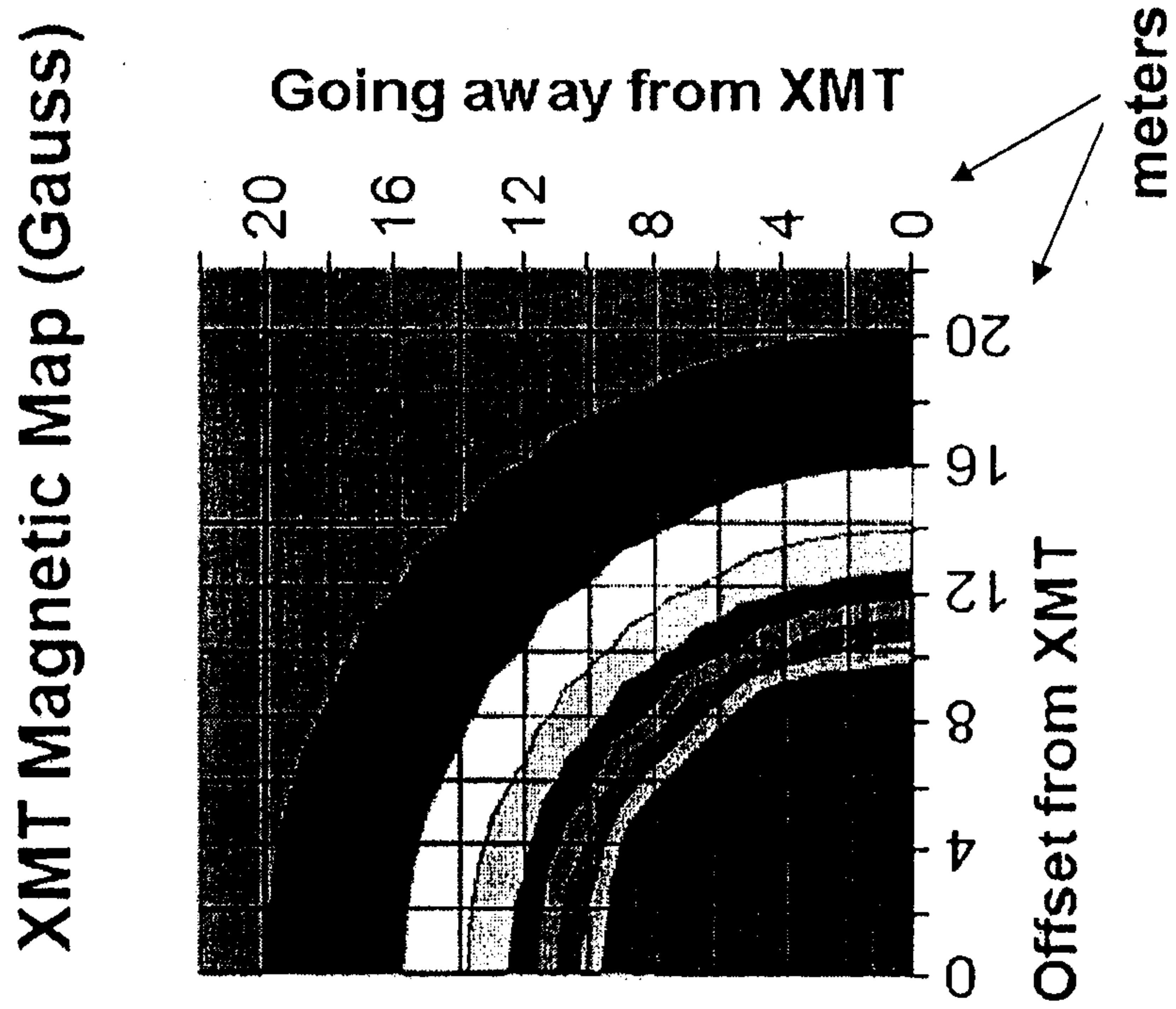


Figure 4:

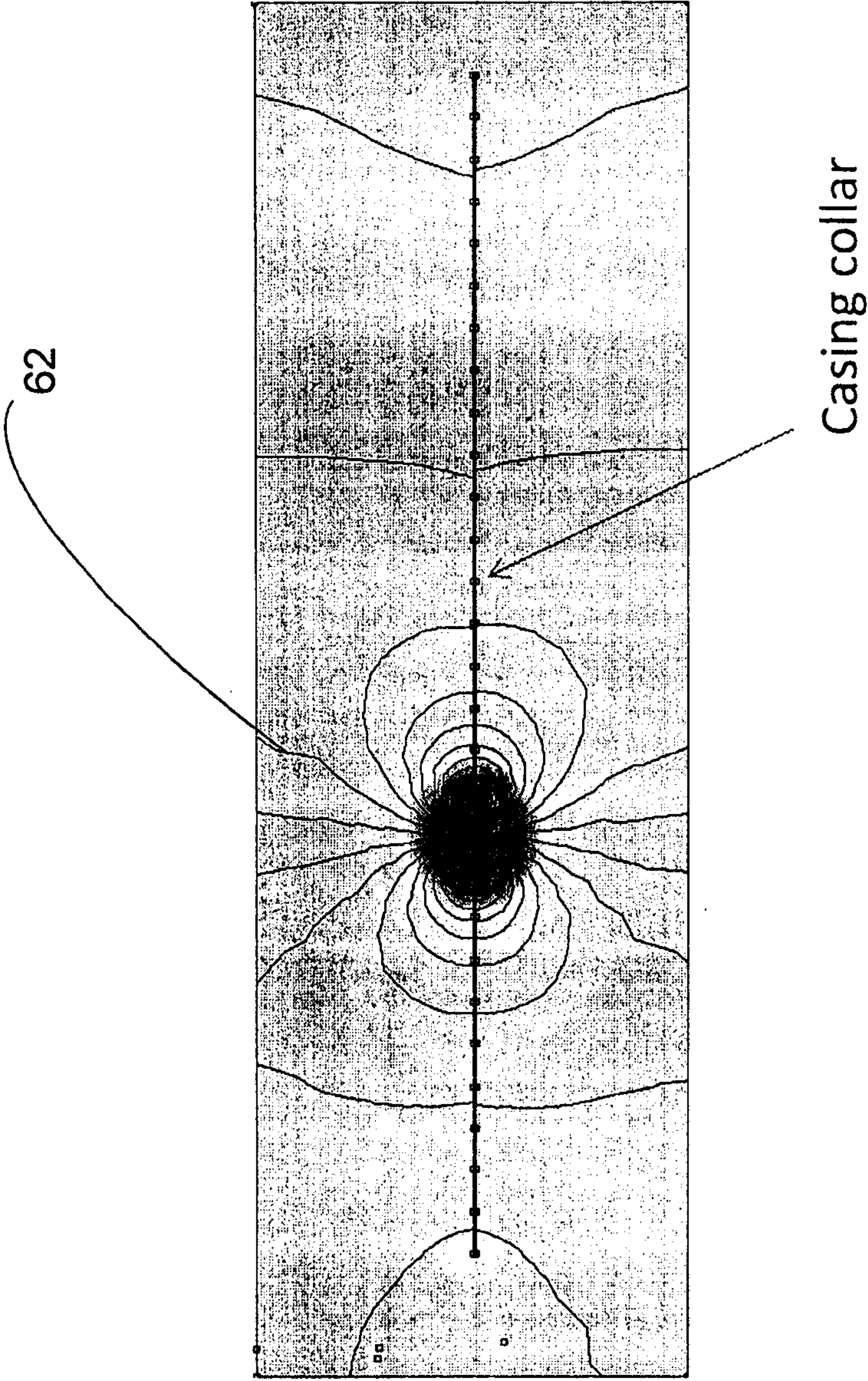


Figure 5A:

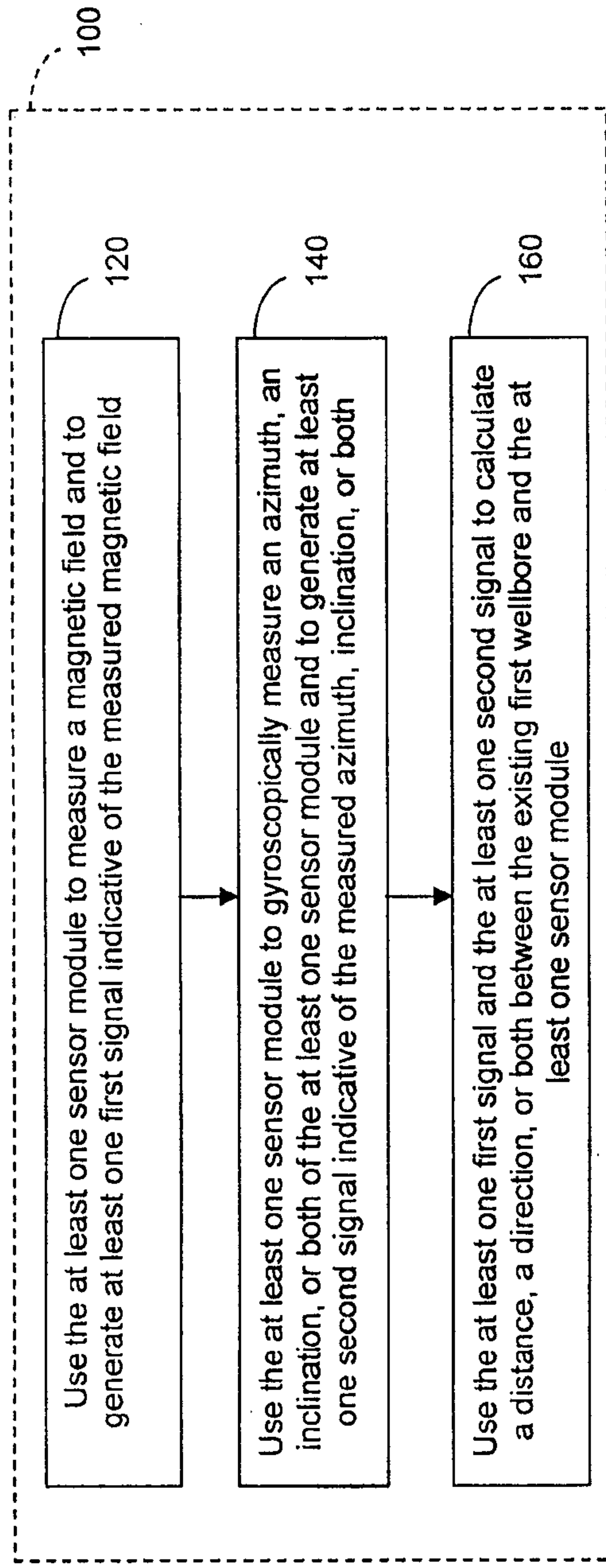


Figure 5B:

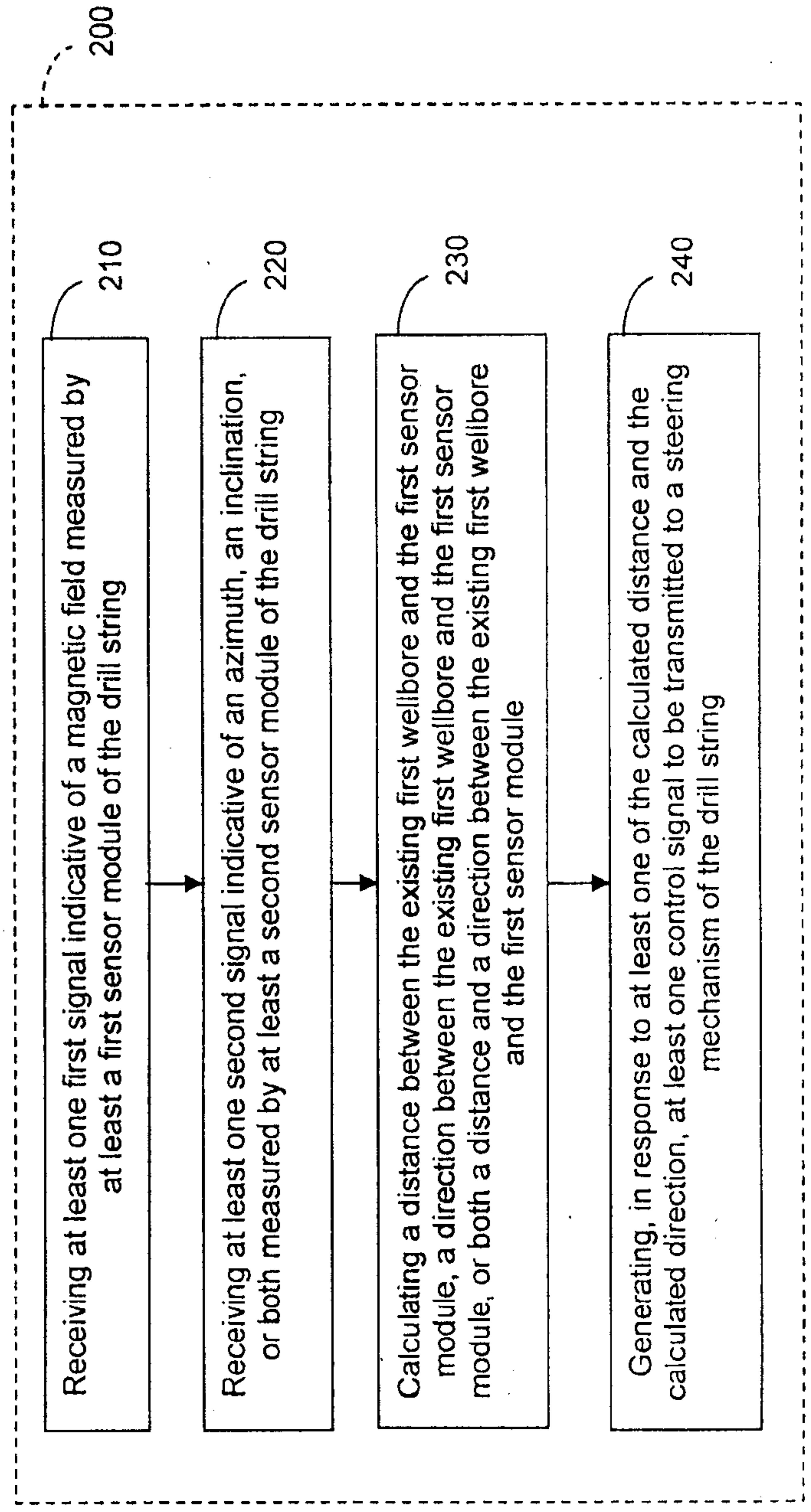


Figure 6A:

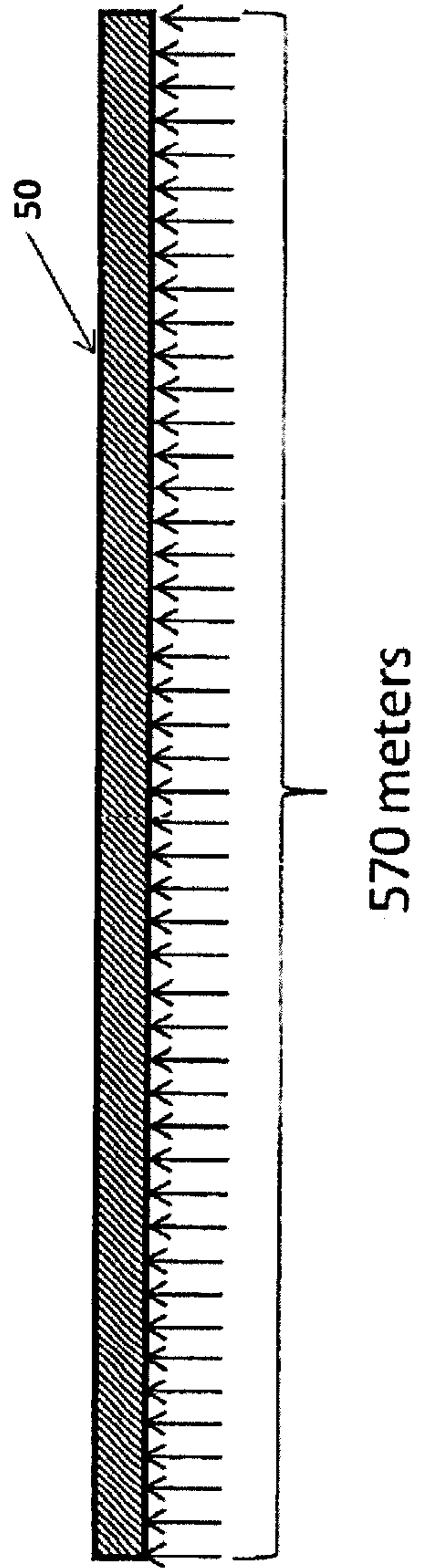


Figure 6B:

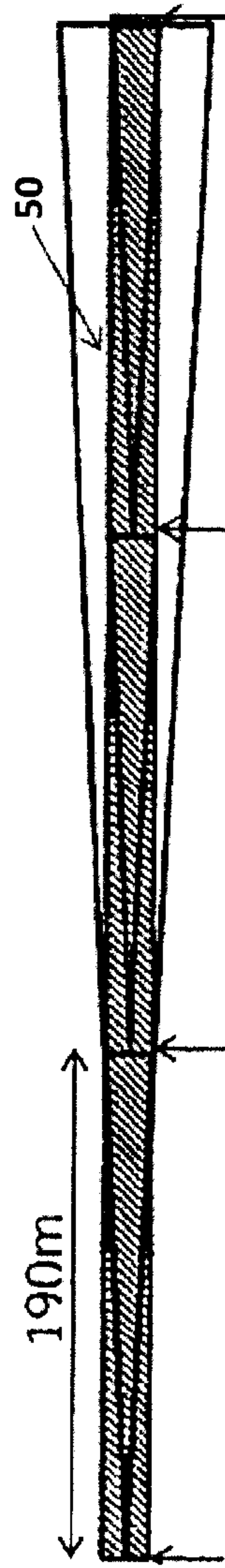


Figure 7:

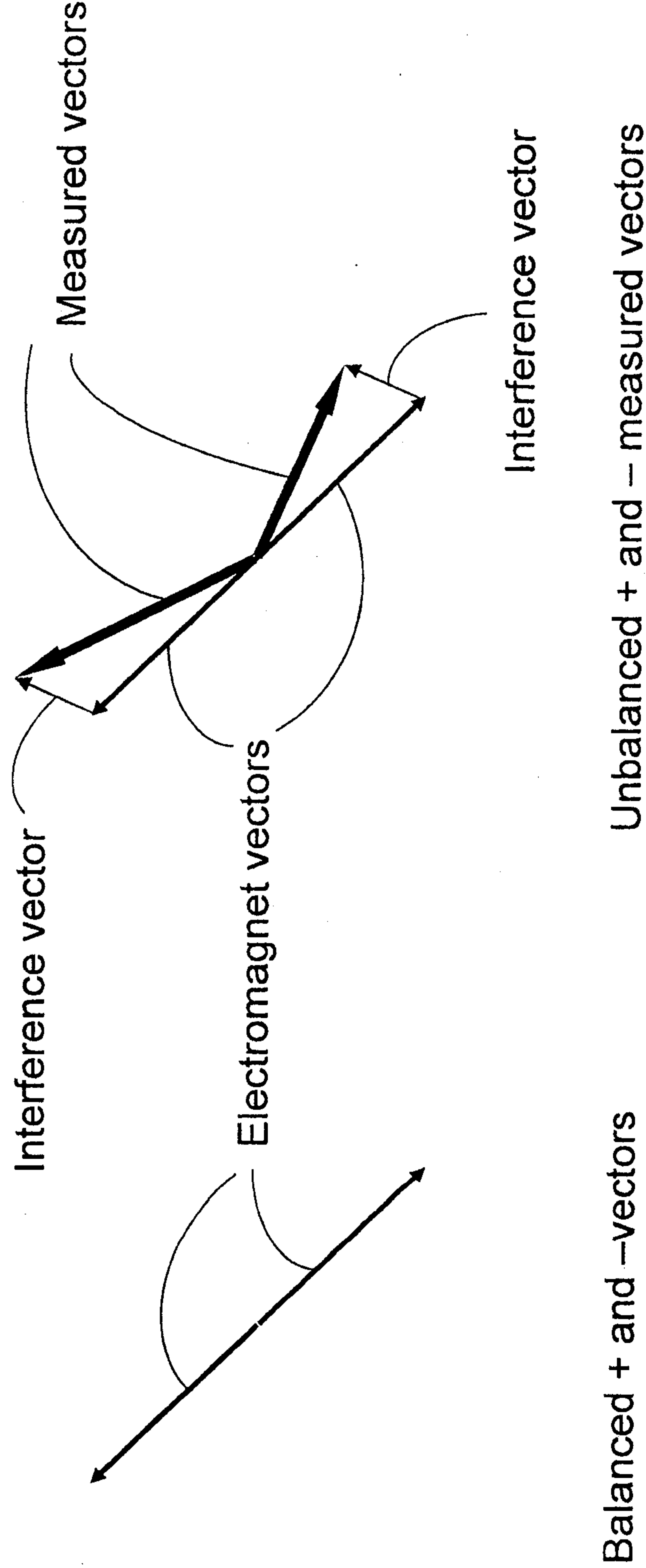


Figure 8A:

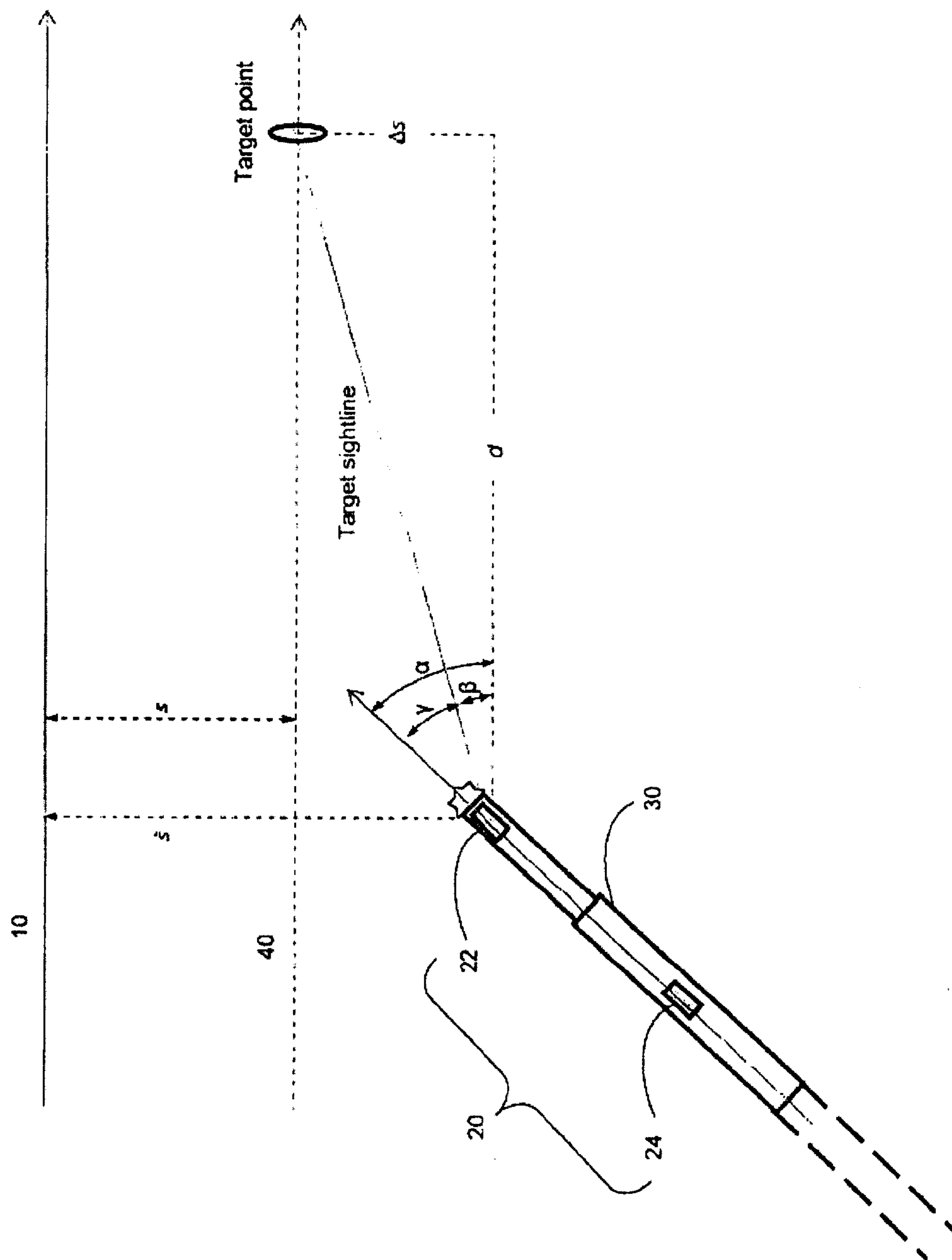


Figure 8B:

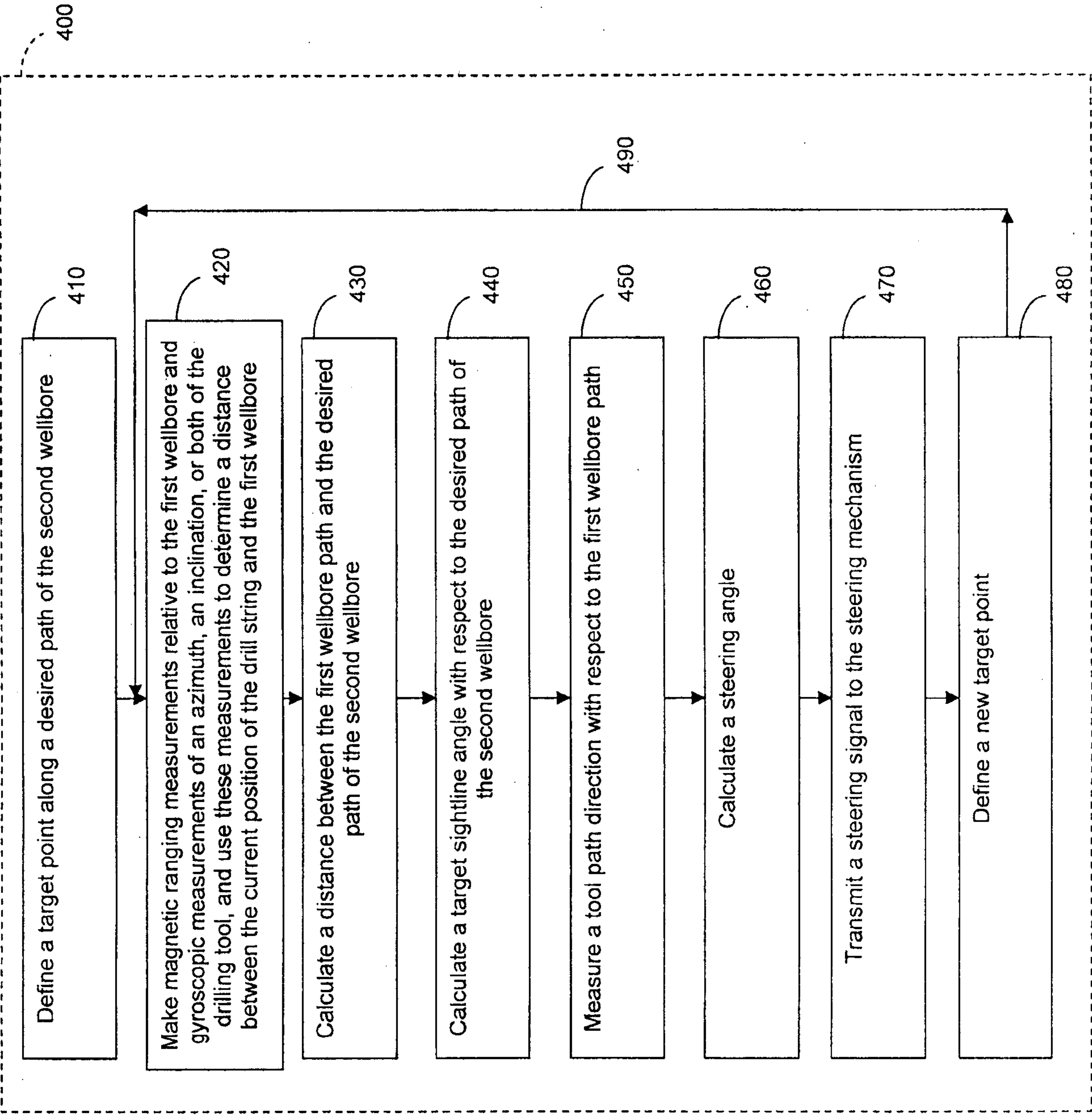


Figure 9:

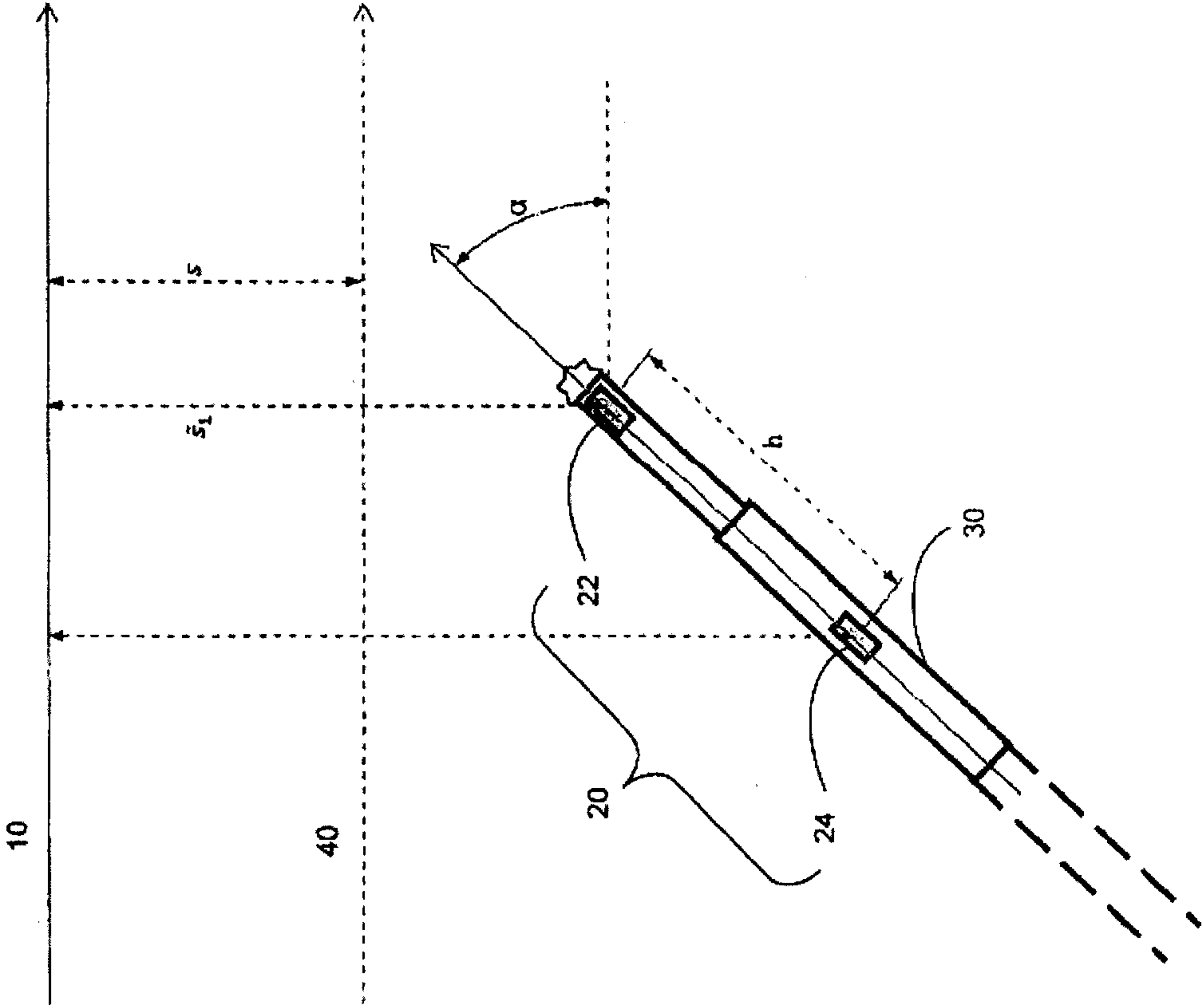
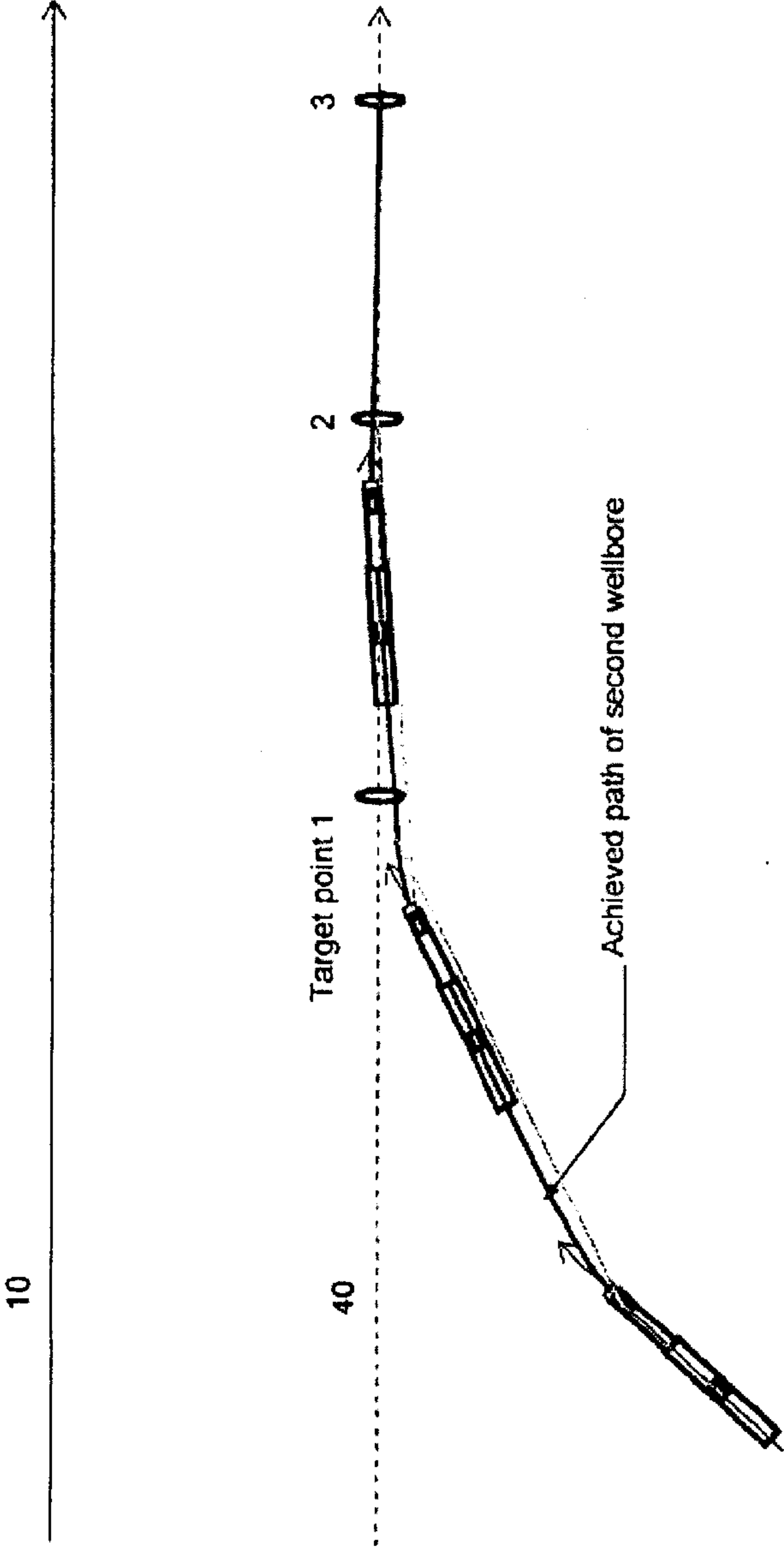


Figure 10:



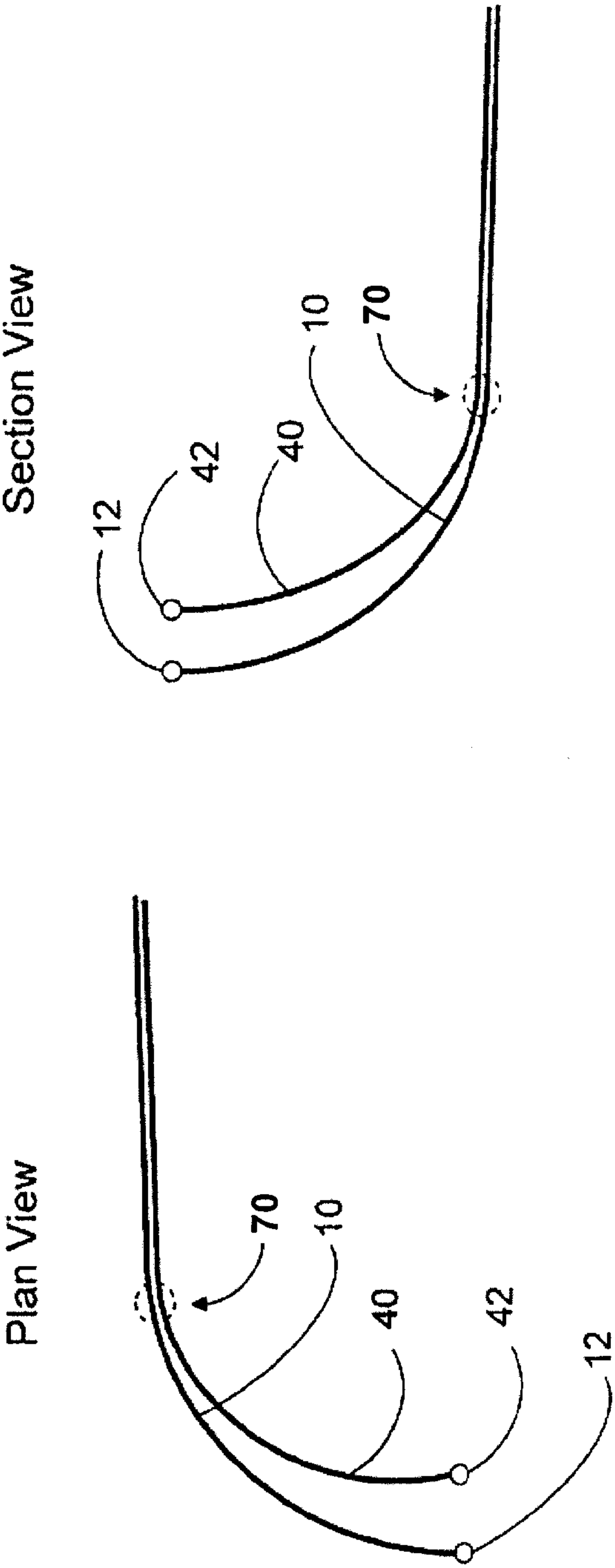


Figure 11:

Figure 12A:

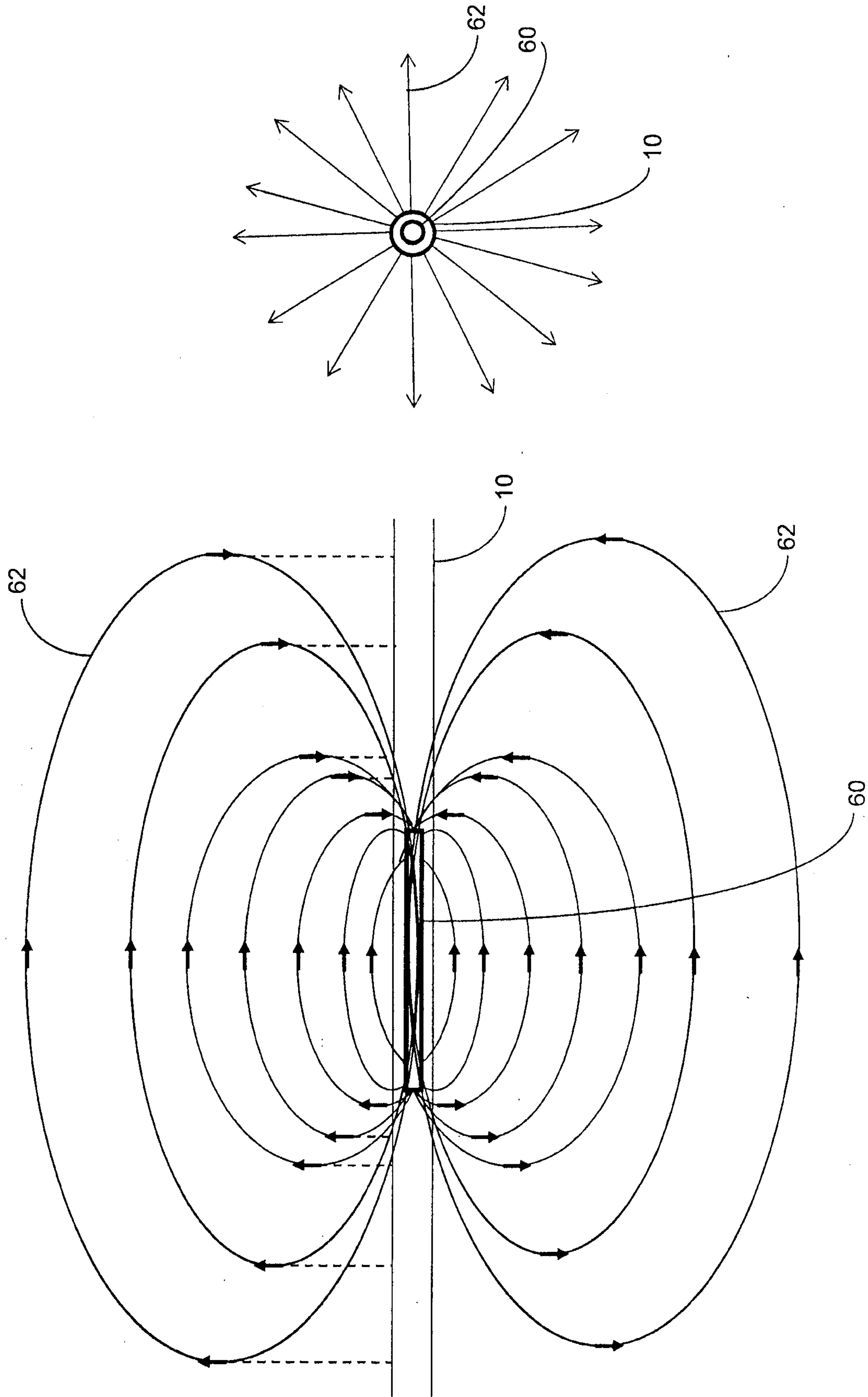


Figure 12C:

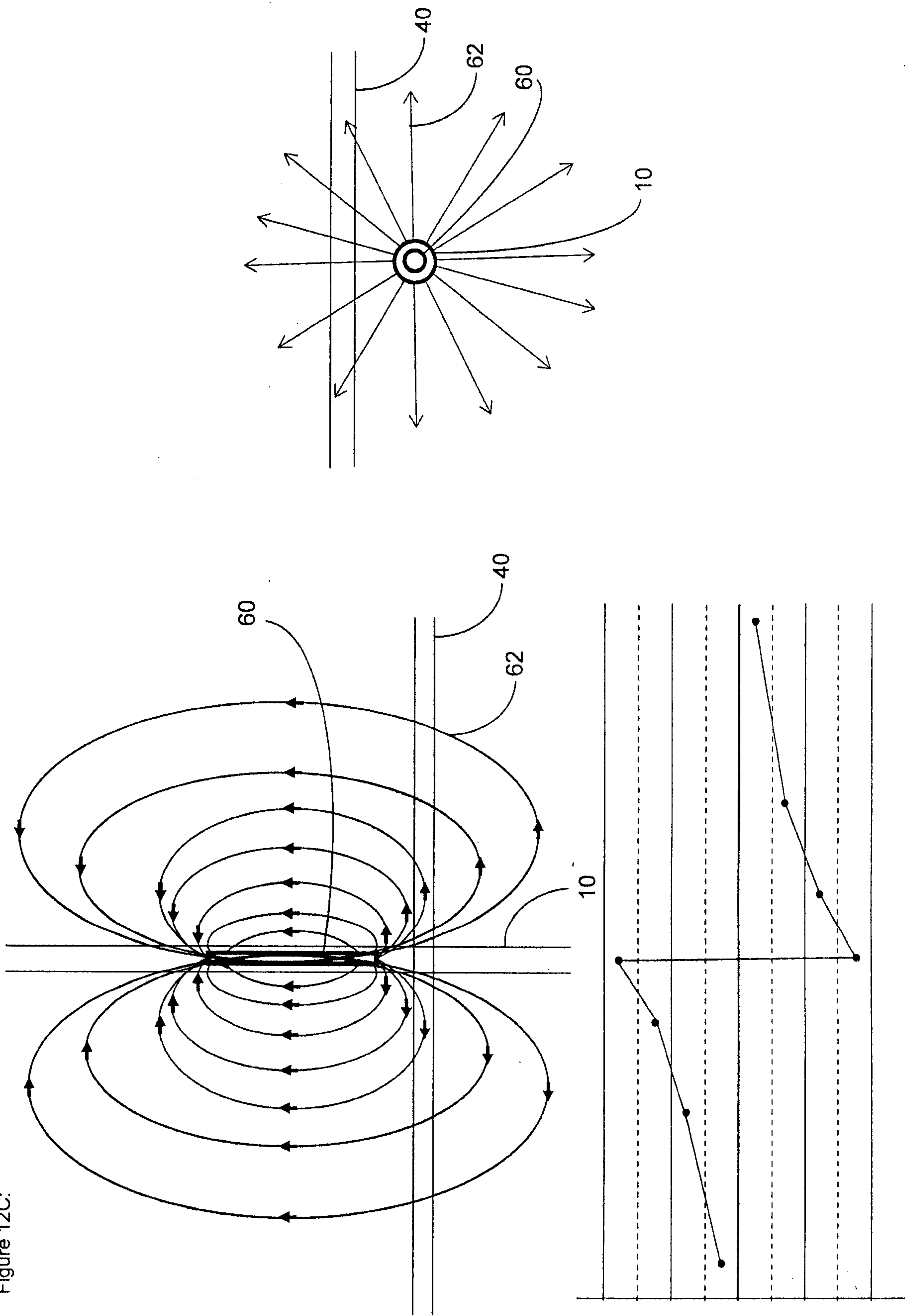


Figure 13A:

		1	2	3
	Start	Finish	Finish	Finish
Total mag. field (nT)	300	300	700	900
Flux angle	300	58	1	290
axial mag. field (nT)	-260	254	12	-846
Gradient Angle (deg./10m)		-24	-30	-1
Gradient axial mag. field (nT/10m)		51	27	-59
Distance to target axis (m)	5.5m	6.7m	5.5m	4.2m

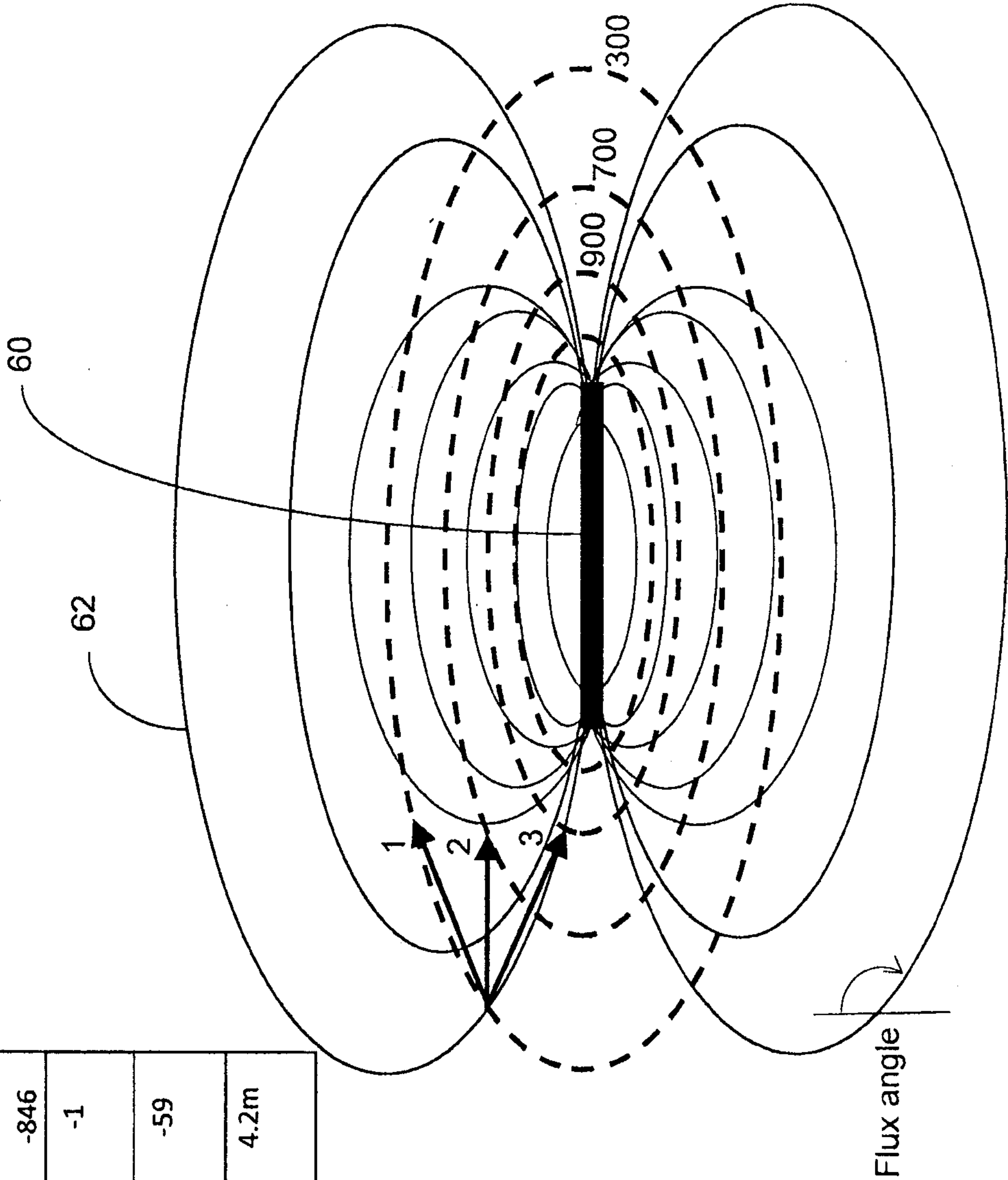


Figure 13B:

	A	B	C	D	E	F
Axial mag. field (nT)	-260	-195	-116	194	613	893
Total mag. field (nT)	300	390	670	750	800	900
Flux angle	300	330	350	15	50	83
Cross axial field (nT)	150	338	660	724	514	110
x-component (nT)	-115	-259	-505	-555	-394	-84
y-component (nT)	96	217	424	466	331	71
Angle of second wellbore to first wellbore (degrees)	310	310	310	310	310	310
Distance from first wellbore (m)	5.71	5.68	5.88	5.56	5.47	5.76

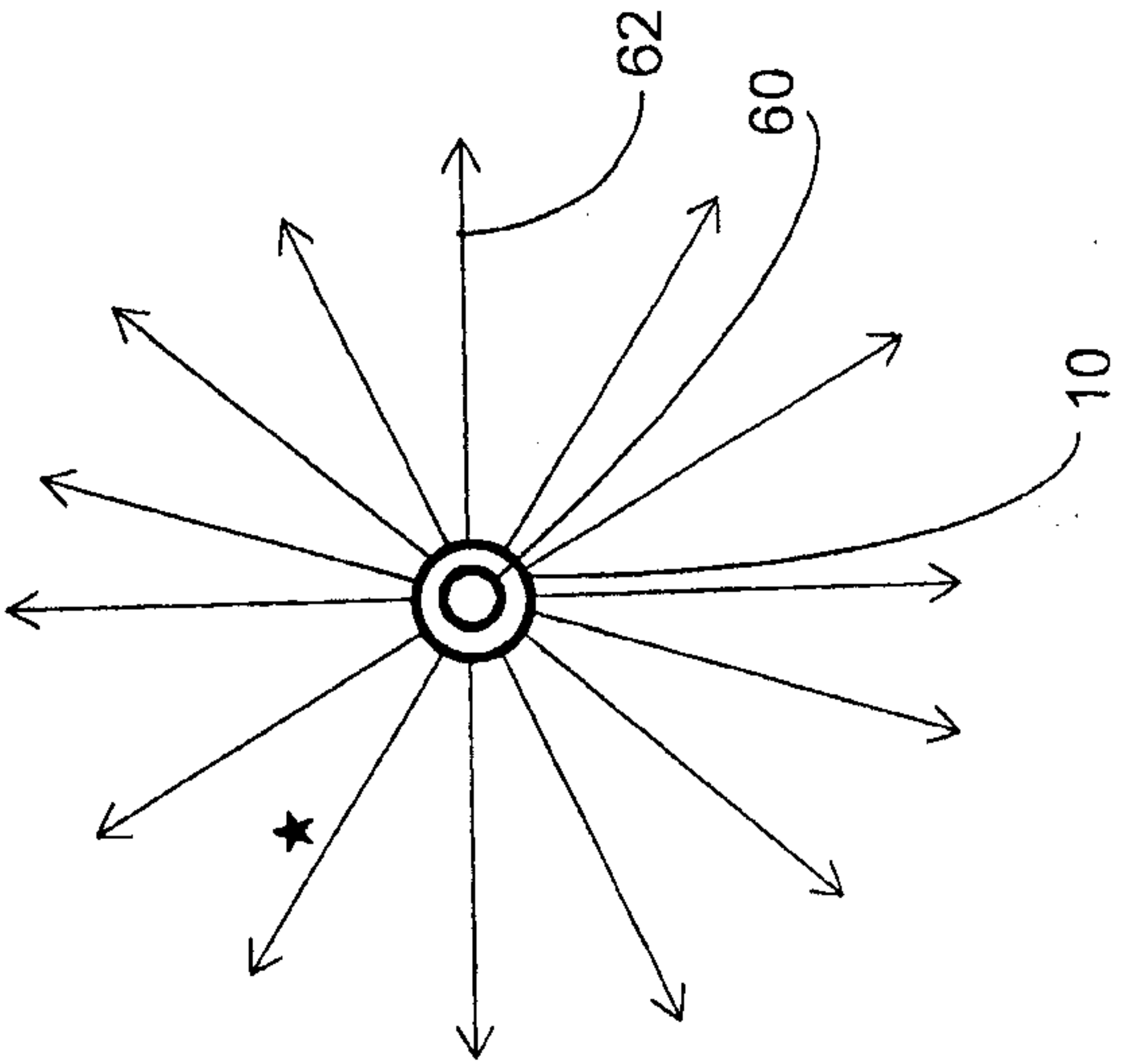
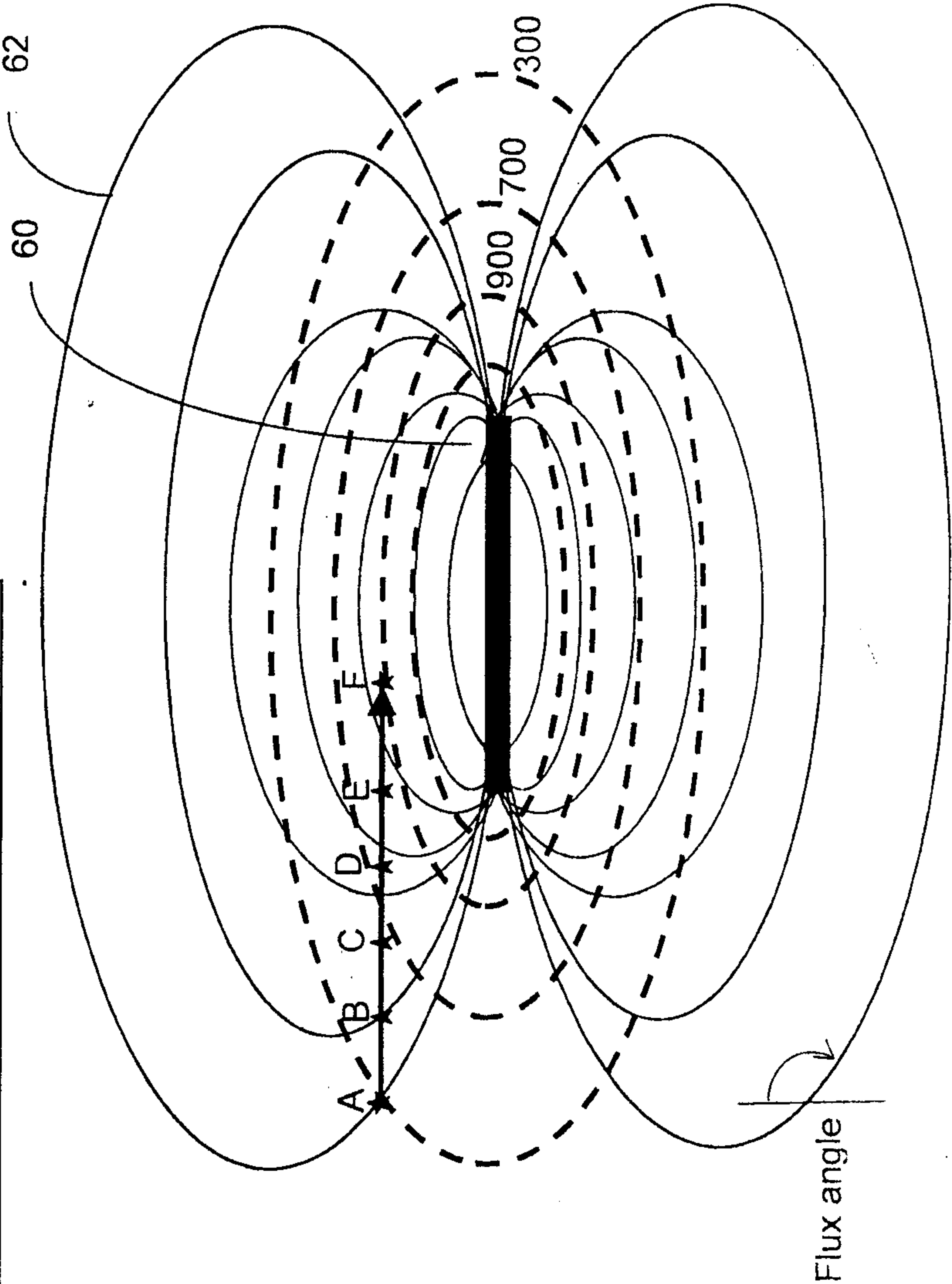


Figure 13C:

	J	K	L	M	N	O
Axial mag. field (nT)	-50	-173	-286	-120	171	115
Total mag. field (nT)	100	200	330	690	500	150
Flux angle	330	300	240	190	160	50
Cross axial field (nT)				-680	-470	
x-component (nT)				-232	-240	
y-component (nT)				-639	-442	
Angle of tool face to first wellbore (degrees)				200	209	
Azimuthal angle of second wellbore to first wellbore (degrees)				80	111	
Distance from first wellbore (m)				7.8	8.1	

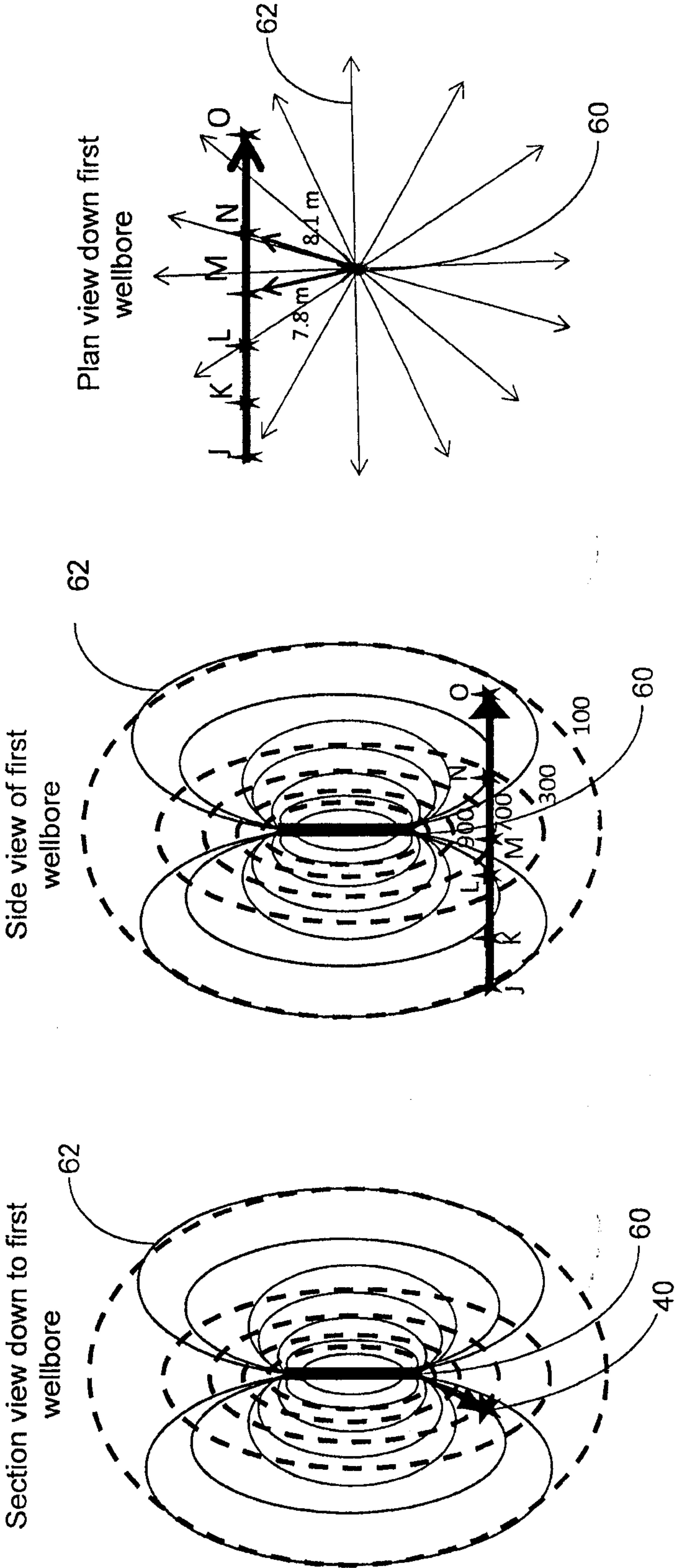


Figure 14:

