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(54) ELONGATED COIL ASSEMBLY FOR ELECTROMAGNETIC BOREHOLE SURVEYING

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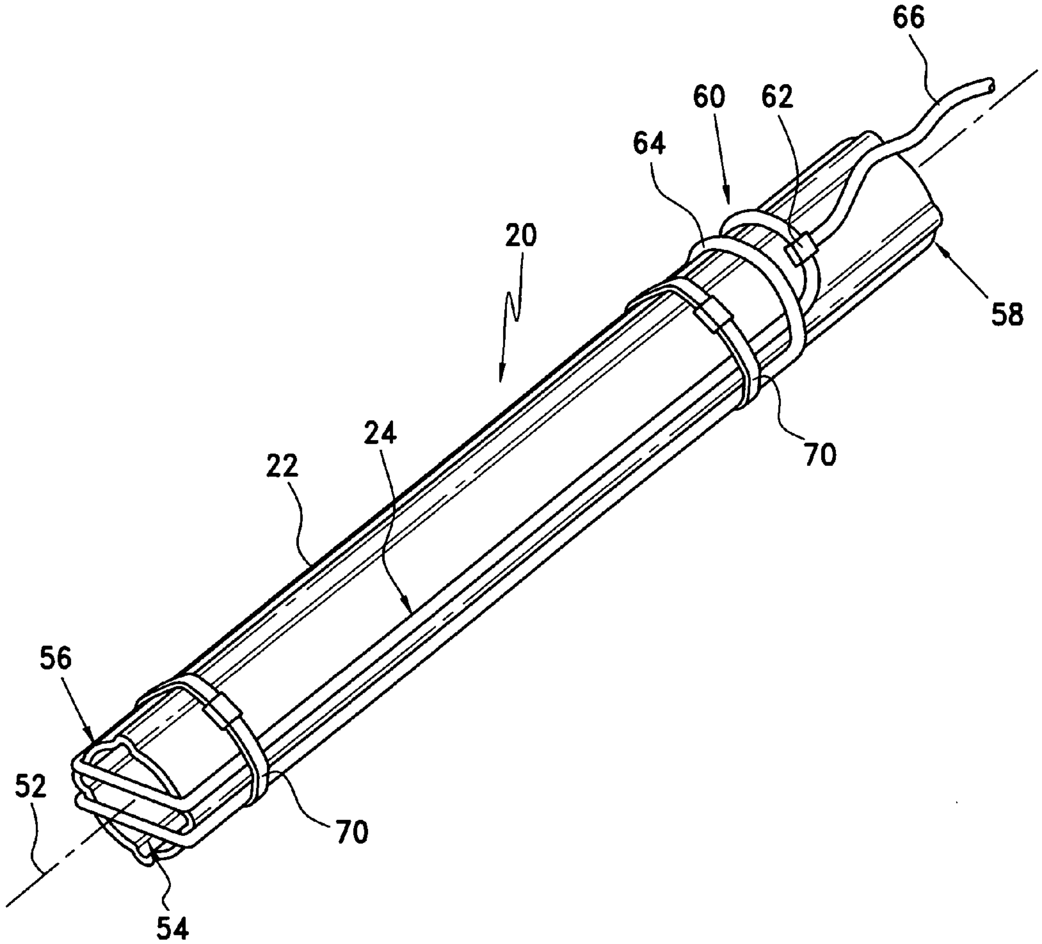
(52) U.S. Cl. **175/24**; 175/45

(57) **ABSTRACT**

An apparatus and method for surveying the path of a borehole includes three single-axis electromagnetic field sensors and three single axis gravity direction sensors in the borehole being surveyed. A pair of closely spaced, parallel guide wires carrying oppositely directed electric current in a reference borehole generate a known electromagnetic field, which is detected by the sensors. Mathematical analysis of electromagnetic and gravity measurements determines the lateral location and the direction of drilling in the neighboring borehole.



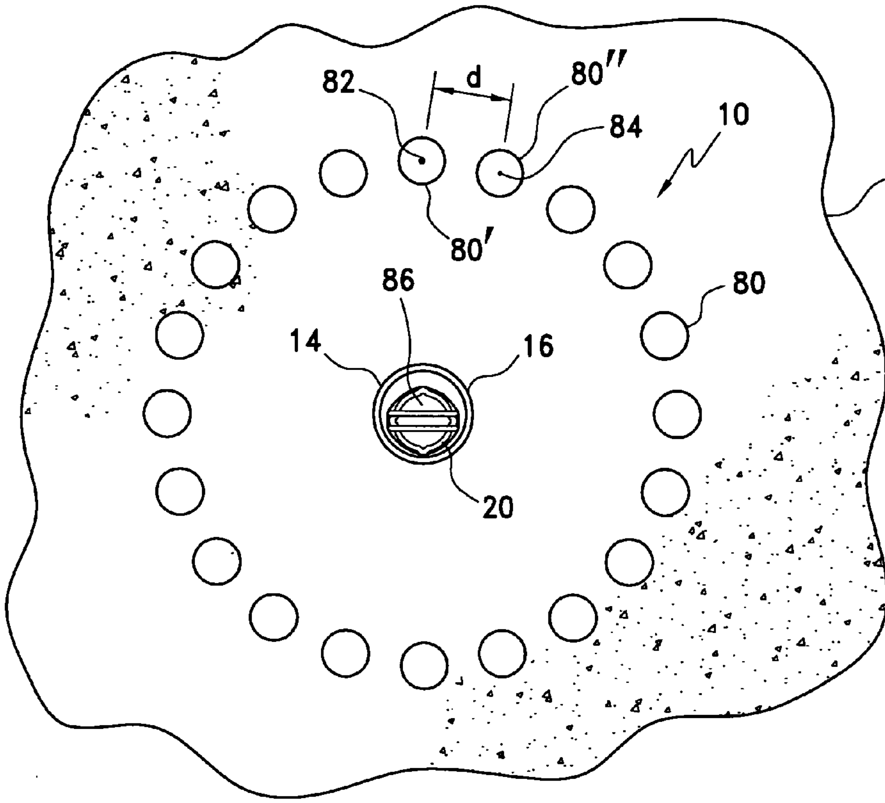

82
d
80''
84
10
12
80'
86
80
14
16
20

FIG. 1

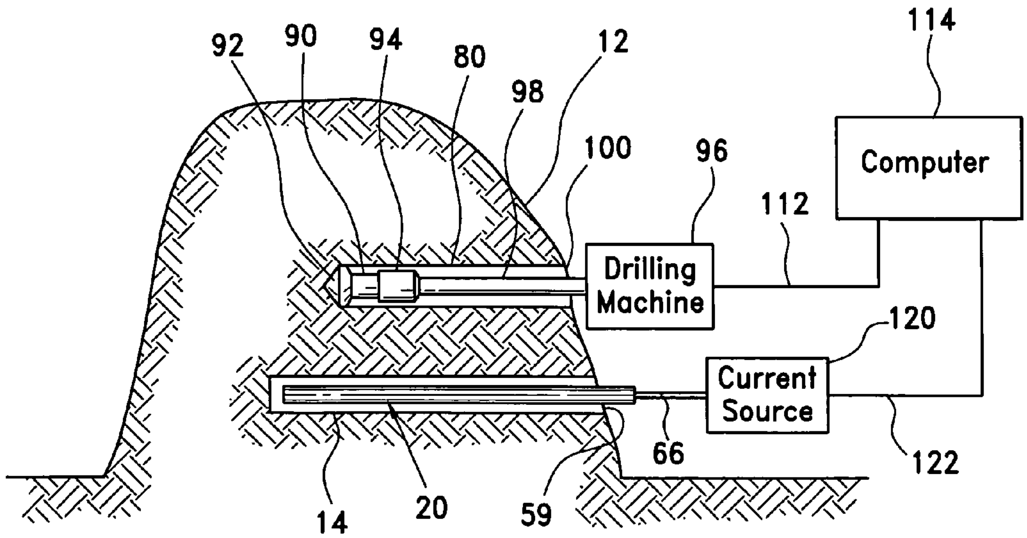

114
92
90
94
80
12
98
100
96
Computer
112
Drilling
Machine
120
Current
Source
66
122
14
20
59

FIG. 6

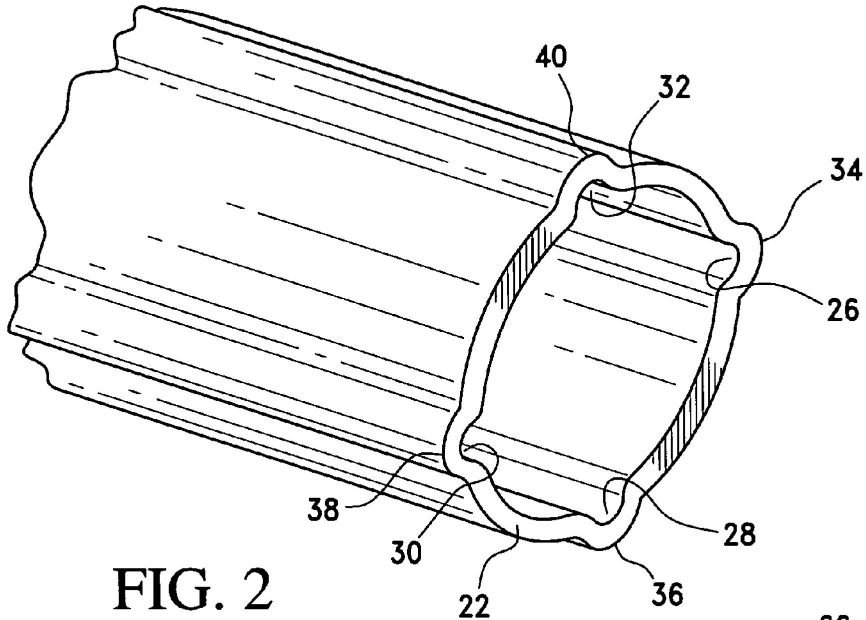


FIG. 2

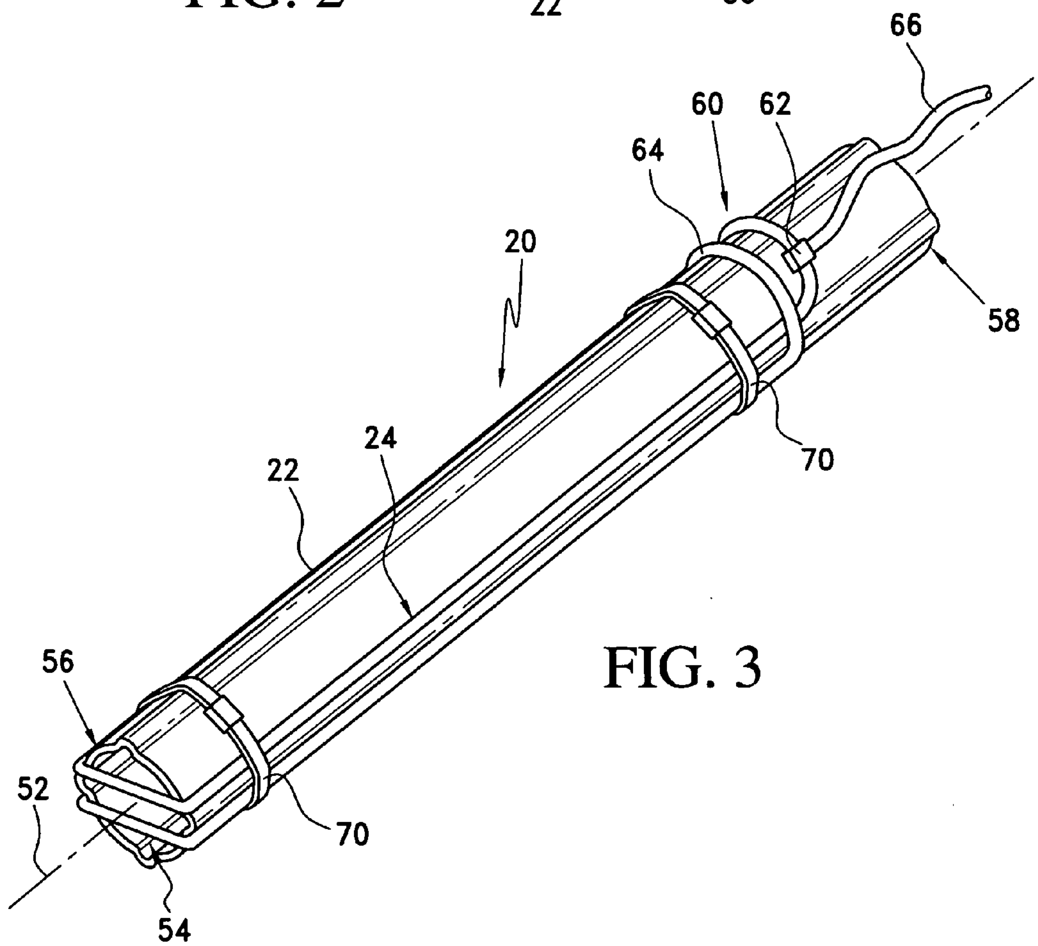


FIG. 3

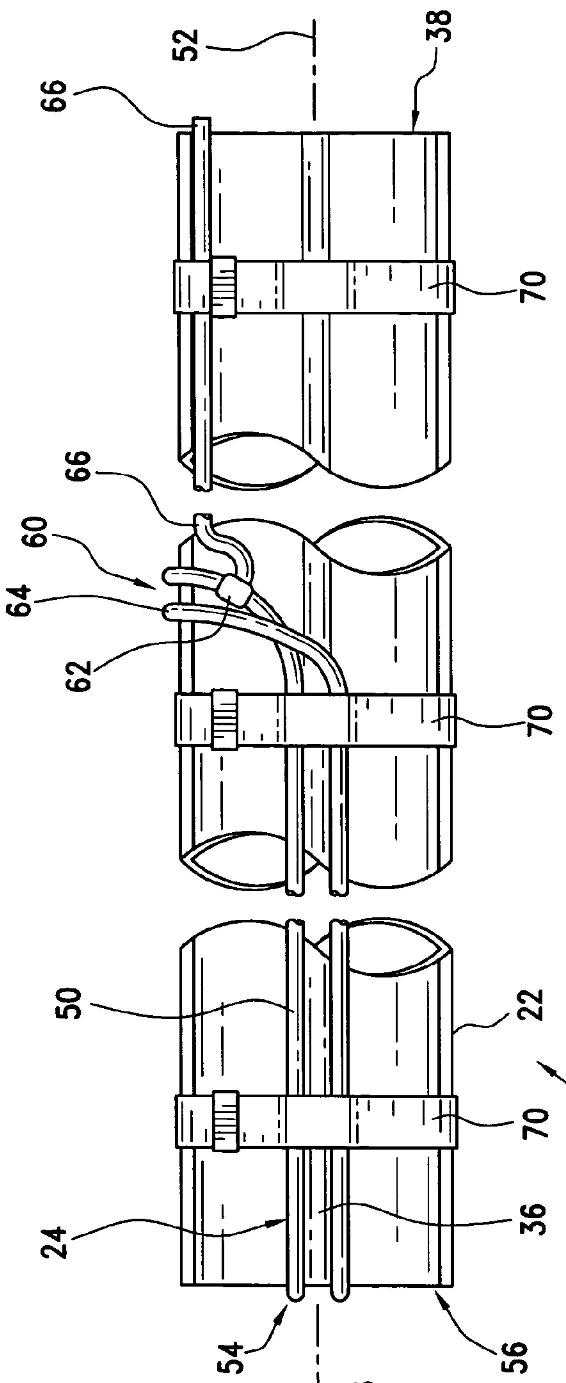

52
38
66
70
66
60
64
62
70
50
22
70
20
24
36
54
56

FIG. 4

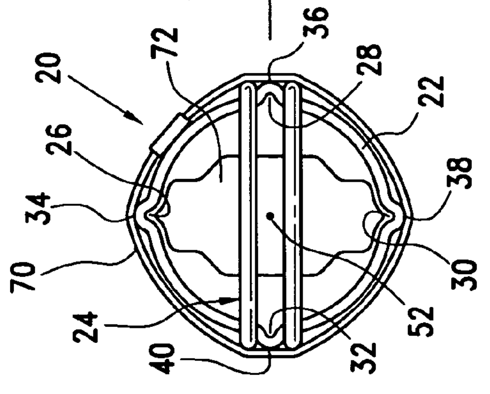

20
72
36
28
22
26
38
34
70
30
24
52
40
32

FIG. 5

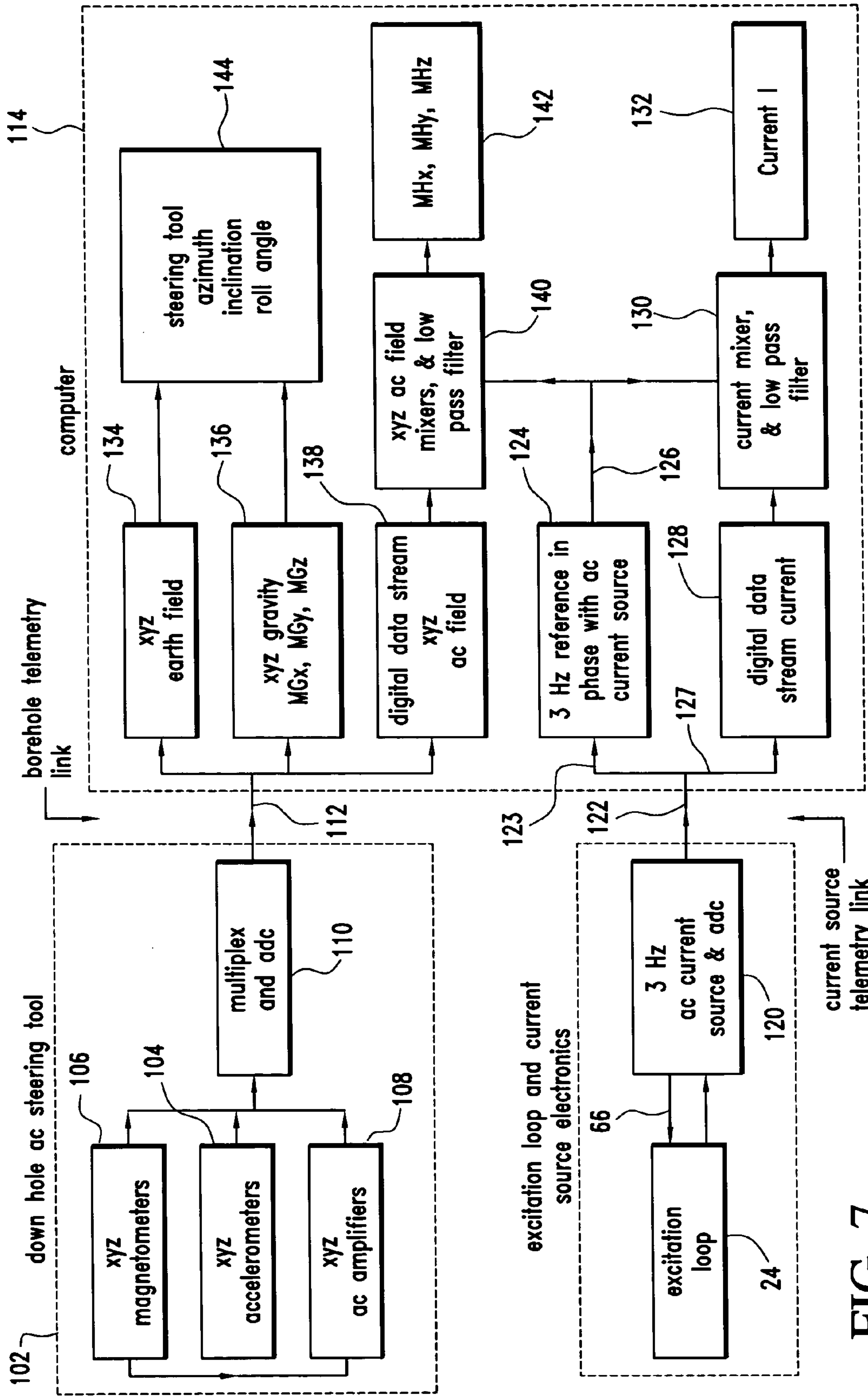

102
down hole ac steering tool
106
104
108
xyz magnetometers
xyz accelerometers
xyz ac amplifiers
multiplex and adc
110
112
borehole telemetry link
114
computer
xyz earth field
134
xyz gravity MGx, MGy, MGz
136
digital data stream xyz ac field
138
steering tool azimuth inclination roll angle
144
xyz ac field mixers, & low pass filter
140
MHx, MHy, MHz
142
3 Hz reference in phase with ac current source
124
126
digital data stream current
128
127
current mixer, & low pass filter
130
Current I
132
123
122
excitation loop and current source electronics
3 Hz ac current source & adc
120
66
excitation loop
24
current source telemetry link

FIG. 7

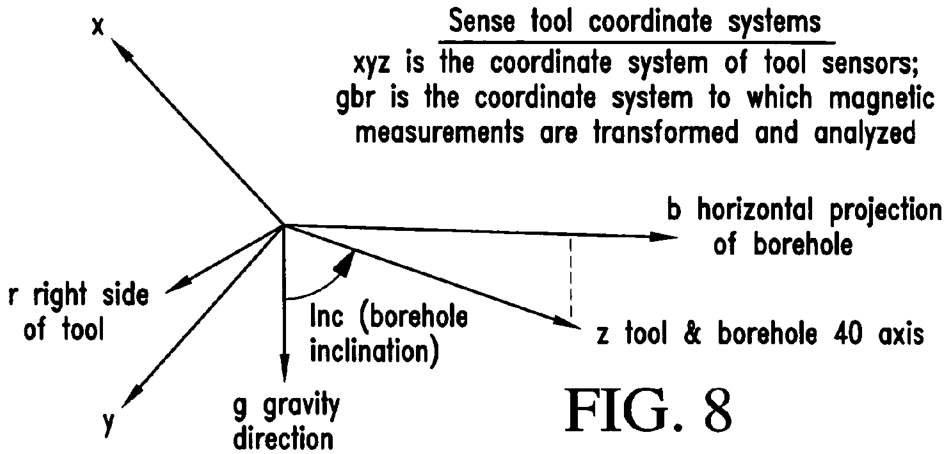


FIG. 8

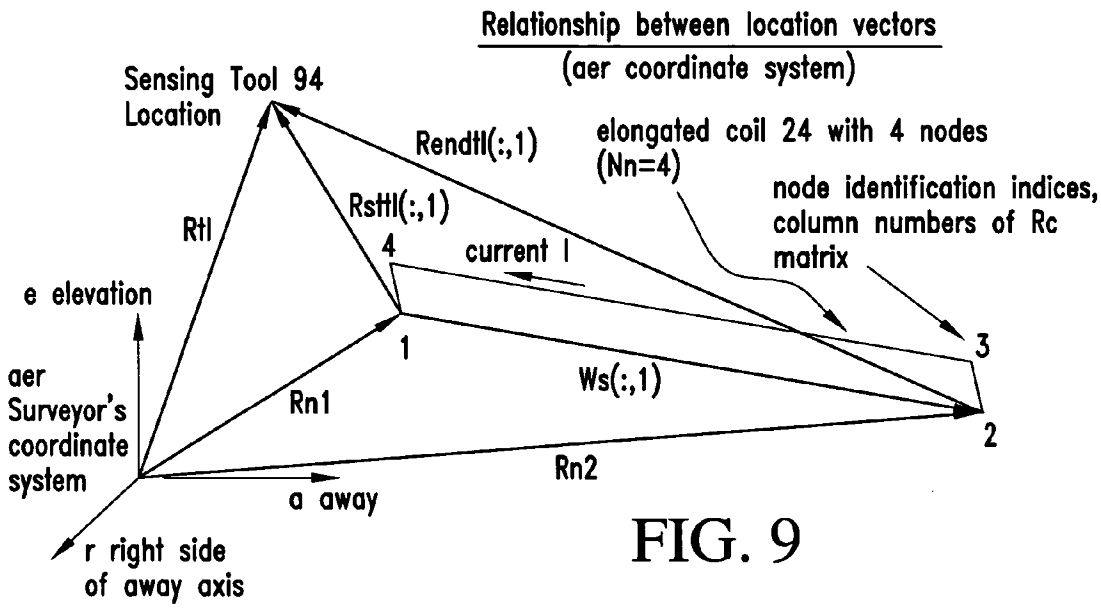


FIG. 9

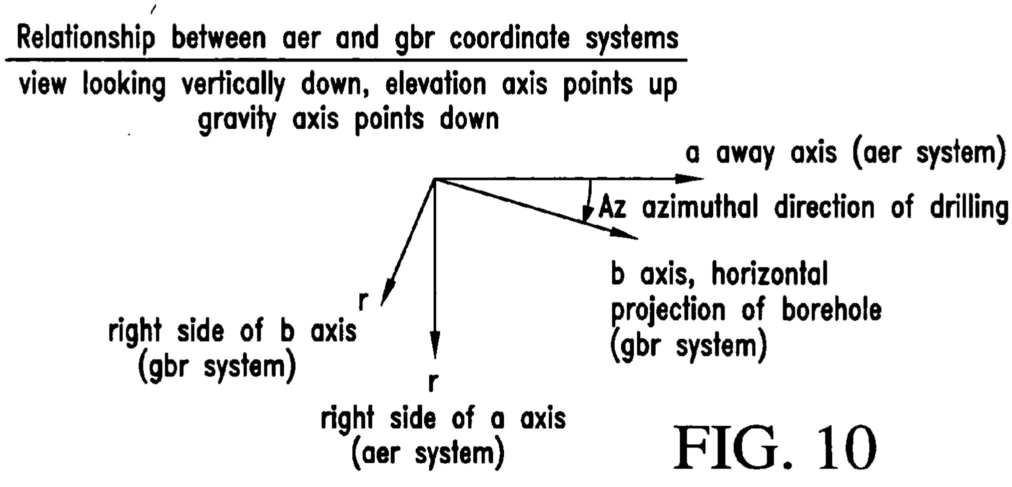


FIG. 10

ELONGATED COIL ASSEMBLY FOR ELECTROMAGNETIC BOREHOLE SURVEYING

BACKGROUND OF THE INVENTION

[0001] This application claims the benefit of U.S. Provisional Application No. 60/555,676, filed Mar. 24, 2004, the disclosure of which is hereby incorporated herein by reference.

[0002] The present invention relates to a method and apparatus for drilling generally horizontal boreholes, and more particularly to a guidance system for drilling such boreholes to a close tolerance along a specified path.

[0003] The technology for drilling boreholes into or through hills or mountains, under rivers, and the like has been well developed over the years. However, unique problems arise when it becomes necessary to drill such a borehole in an area that is inaccessible, such as beneath a ship's channel in a river, or where multiple boreholes must be drilled parallel to each other with a high degree of accuracy. In such situations, ordinary techniques for guiding the drilling of boreholes are not always satisfactory.

[0004] An example of the need for a high degree of accuracy in drilling boreholes is found in a recently developed procedure for boring horizontal tunnels in unstable earth. This procedure requires drilling a number of parallel boreholes of small diameter with a high degree of accuracy around the circumference of the proposed tunnel. The boreholes may be, for example, 150 mm in diameter, with about 40 boreholes positioned around the circumference of the tunnel to form a circle of boreholes about 20 meters in diameter. The holes are drilled into the region, such as a hill or mountain, in which the tunnel is to be excavated, and each hole is cased with steel pipe. Refrigerant is then pumped through the casings for an extended period, for example, one month, to freeze the soil. Thereafter, the earth inside the circle formed by the boreholes is excavated using conventional techniques to produce a tunnel in which frozen earth temporarily holds the tunnel excavation open until a permanent supporting structure of concrete or steel is put into place.

[0005] A major problem with the forgoing technique is the need to drill a large number of boreholes around the circumference of a tunnel while keeping the boreholes accurately spaced and parallel to each other so as to properly define the tunnel along its entire length and with the spacing between adjacent boreholes being substantially constant to ensure that the freezing process will produce a continuous shell around the location where the tunnel is to be excavated.

[0006] One approach to solving the problem of drilling spaced, parallel boreholes has involved the use of grids on the surface of the earth for producing magnetic fields to guide the borehole drilling, but if access to the surface above the borehole is not available, this technique cannot be used effectively. The guidance fields produced by such grids also have a limited range and may not be effective if the borehole being drilled is too deep. In an urban environment it is often not possible to lay the desired grid on the surface of the earth along the path of the boreholes because of buildings, roads etc. In addition, the presence of large amounts of steel, which is often present between the surface and the desired tunnel path, severely limits these methods. Therefore, an improved technique for drilling parallel boreholes is needed to overcome these shortcomings.

[0007] Another approach for achieving the required parallel drilling has been to drill a sacrificial borehole, for example, in the center of a desired tunnel, using, for example, gyroscopic methods for surveying. A single current-carrying wire is then deployed into this borehole and is connected electrically to a ground at its far end. This method can work well, though it may suffer from difficulties in making the required ground connection, for the method depends upon a uniform flow of return current in the ground. Often it is not possible to achieve a uniform flow, and any uncertainty in the return current flow means that highly accurate boreholes cannot be guaranteed.

[0008] Thus, there is a need to provide a simple, easy-to-use, effective and accurate method and system for guiding the drilling of boreholes, and more particularly to guiding the drilling of boreholes that follow a predetermined path within small tolerances and in any location.

SUMMARY OF THE INVENTION

[0009] The present invention is directed to a method and apparatus for drilling boreholes along predetermined paths, and particularly for boring multiple generally horizontal boreholes along linear or curved predetermined paths with a high degree of accuracy. More particularly, the invention is directed to a guidance system for drilling one or more linear or curved boreholes along predetermined paths at locations spaced from a reference guide path, and, when multiple parallel boreholes are drilled, will be parallel to each other within a tolerance of plus or minus a third of a meter over an indefinite length. In accordance with a preferred form of the present invention, one or more boreholes are drilled from known starting points along desired paths with a high degree of accuracy through the use of an elongated electromagnetic field source coil deployed in a reference borehole.

[0010] The system includes a source coil assembly that is fabricated by winding a wire longitudinally around a tubular carrier so the coil windings extend along diametrically opposite sides of the carrier. The assembly is then deployed in the reference borehole. The roll angle of the coil in the reference well is determined by making inclinometer measurements inside the tubular carrier or, if the carrier is short enough, by noting its roll angle where it enters the reference borehole.

[0011] An alternating current of a few amperes is passed through the coil. Measurements are made of the resulting alternating electromagnetic field and of the direction of gravity near a drill tool in a borehole being drilled. Mathematical analysis of these measurements at a single drill tool location suffices to determine the lateral location of the drill and the azimuth of the direction of drilling. Analysis of data from two locations allows the additional determination of the "away distance" component of the location; for example, the distance from the borehole entry to the drill bit.

[0012] The measurements and data generated by the method and apparatus of the invention provides a system for drilling one or more generally horizontal boreholes in closely spaced relationship to a predetermined path.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] The foregoing, and additional objects, features and advantages of the present invention will become apparent to those of skill in the art from a consideration of the following detailed description of preferred embodiments thereof, taken in conjunction with the accompanying drawings, in which:

[0014] **FIG. 1** is an end view of a tunnel site, illustrating a central guide borehole and a multiplicity of surrounding boreholes defining the circumference of the tunnel;

[0015] **FIG. 2** is a diagrammatic illustration of a tubular carrier on which conductors are wound to form an elongated coil;

[0016] **FIG. 3** is a diagrammatic perspective view showing the construction of an elongated coil and carrier assembly;

[0017] **FIG. 4** is a side elevation of the coil assembly of **FIG. 3**;

[0018] **FIG. 5** is an end view of the coil assembly of **FIG. 3**;

[0019] **FIG. 6** is a diagrammatic cut-away side elevation view of a guide borehole and a parallel borehole being drilled using the elongated coil assembly of **FIG. 3**, in accordance with the invention;

[0020] **FIG. 7** is a schematic block diagram of electronic circuitry for the system of the invention;

[0021] **FIG. 8** is a diagrammatic illustration showing the relationship between sensor xyz and borehole gbr coordinate systems;

[0022] **FIG. 9** is a diagrammatic illustration showing the relationships of the location vectors of sensor tool location and wire segments constituting the elongated coil in a surveyor's aer coordinate system;

[0023] **FIG. 10** is a diagrammatic illustration showing the relationship between the gbr and the aer coordinate systems.

DETAILED DESCRIPTION

[0024] Turning now to a more detailed description of a preferred embodiment of the present invention, there is illustrated in **FIG. 1 a** drilling site **10** located in a ground feature **12**, such as a hillside, a mountain, or other entryway for one or more generally horizontal boreholes. In the embodiment illustrated in this figure, a plurality of parallel, spaced boreholes defining the circumference of a tunnel to be excavated are illustrated, although it will be understood that the techniques described herein may be used for guiding the drilling of any number of boreholes. In this embodiment, a reference, or guide borehole **14** is first drilled into the earth using known drilling, borehole guidance and logging techniques. The guide borehole may be drilled in a straight line into the side of a mountain, as illustrated in **FIG. 6**, for example, or may be curved, as when drilling under an obstacle such as a river, lake, or the like, in known manner. The guide borehole preferably is cased with a plastic pipe **16**, and preferably is approximately 150 millimeters in diameter.

[0025] After the guide borehole **14** has been drilled along the desired path of the excavation, or adjacent the path of one or more parallel boreholes to be drilled, a carrier assembly **20** such as that illustrated in **FIGS. 3 through 6** is installed in the guide borehole. The carrier assembly includes an elongated core **22** on which is wound a longitudinal coil **24**, to be described in greater detail below. The core element is generally tubular, and preferably an ABS plastic. A particularly suitable core is a plastic tube known as "inclinometer tubing" and manufactured by SIREG, SpA which, as illustrated in **FIG. 2**, is approximately 90 millimeters in diameter and is fabricated with a plurality of grooves, such as the fourgrooves **26**, **28**, **30** and **32** and corresponding ridges **34**, **36**, **38** and **40** on the outside of the pipe at the locations of the groove. The grooves and ribs are equally spaced around the circumference of the tube, with grooves **26** and **20** and grooves **28** and **32** being diametrically opposed to each other. The grooves on the inside of the core permit an inclinometer to be deployed along the length of the core to measure the roll angle of the core as it is inserted into a borehole, and thus to determine the roll angle of the coil wound on the core, while the ridges on the outside surface of the core serve as guides for securing the coil.

[0026] The coil **24** is formed by wrapping multiple turns of a wire cable **50** longitudinally around the core using opposed ridges such as the ridges **36** and **40** to align the coil with the longitudinal axis **52** of the core. The coil **24** preferably incorporates five or more turns of a wire conductor which may pass around both ends of the core, as illustrated at **54** at a first end **56** of the core. Alternatively, in the illustrated preferred embodiment, the coil does not pass around the second end **58** of the core, but instead stops short of end **58**, with the cable passing over the core as illustrated at **60** in **FIGS. 3 and 4** to provide a continuous coil. Thus, for example, a first turn of the coil begins at a connector **62**, extends along the left hand side of core **22**, (as viewed in **FIG. 3**), crosses the core at end **56**, extends along the right-hand side of the core (as viewed in **FIG. 3**) to the region of the connector to complete a first turn of the coil. The conductor loops over the core as at **64**, again extends along the length of the core, crosses over the end **56**, and extends back along the length of the core to connector **62**, to complete a second turn. Any desired number of turns are provided, and the free ends of the coil are fastened, at connector **62**, to a supply cable **66** that extends out of the borehole. The longitudinally extending coil **24** is wrapped around the core adjacent diametrically opposed ridges such as ridges **36** and **40** and are secured by crimped stainless steel straps **70** spaced along the length of the assembly every half meter or so. Although only two turns are illustrated in the figures, any number of turns may be provided; it is usually desirable to make up a multi-turn coil rather than using a single turn loop for power supply impedance matching purposes. The end **58** of the core extends beyond the coil and additional lengths of core may be connected to it so that the coil **24** can be positioned at an appropriate depth within the guide borehole **14** with respect to the drilling which is to take place. The carrier assembly may be constructed as it is being inserted into the guide borehole, if desired.

[0027] When the coil assembly **20** is inserted into a guide borehole, some twisting may occur, so it is desirable to measure its roll angle by means of a steering tool or an inclinometer which may be positioned in, and moved along, the internal grooves of the tubing **22**, as illustrated at **72** in **FIG. 5**. The inclinometer may be moved along the length of the core **22** after the coil assembly has been installed in the guide hole, with measurements being taken along the length of the coil. Normally a precise gyroscopic hole survey is made for the reference guide borehole before the coil assembly is inserted. If such a survey is not available, and if the earth's magnetic field is not severely distorted by nearby steel, a survey may be constructed at the same time that the roll angle of the core is measured by noting at each point of measurement the inclination and azimuth and the earth's magnetic field as a function of depth. With these measurements, a precise wire file can be made, giving precise wire coordinates of the elongated coil in the guide borehole as a function of depth, and from this file the magnetic field produced by a known current in the coil can be computed for any point in space.

[**0028**] After the guide borehole, such as the borehole **14**, has been drilled and preferably surveyed, the coil assembly **20** is placed in it and positioned to produce a magnetic field for use in guiding the drilling of one or more additional boreholes, such as the borehole **80** illustrated in **FIG. 6**. In the case where multiple boreholes are to be drilled around the circumference of a region that is to be excavated to form a tunnel, such as the tunnel arrangement illustrated in FIG. **1**, the boreholes **80** may be 150 millimeters in diameter and drilled with their center axes spaced 1½ meters apart. Thus, as illustrated in **FIG. 1**, adjacent boreholes, such as the boreholes **40**' and **40**" are drilled along paths having parallel axes **82** and **84** that are spaced apart by a distance d, where d is about 1½ meters. The resulting tunnel would have a radius of about 10 meters between the axis **86** of guide borehole **14** and the axis **82** of borehole **80**', for example. Different borehole diameters and spacing may be utilized for different tunnel sizes, as will be apparent to those of skill in the art.

[**0029**] As illustrated in **FIG. 6**, the boreholes **80** are drilled directionally by a drill tool **90** that incorporates a drill bit **92** and steering tool package **94** in known manner. The package **94** includes provisions for directional control of the drilling direction and for the measurement of AC electromagnetic fields and the direction of gravity, utilizing conventional magnetometers and accelerometers. A suitable drilling machine **96** drives the drill bit **92** through a shaft **98** in known manner to produce the borehole **80** in the desired location. The exact location of the borehole is regulated in accordance with the measurements made in the steering tool package, as will be explained below.

[**0030**] The usual procedure for drilling such a borehole is to alternately determine, electromagnetically, the location and direction of drilling, to make an adjustment to the face of the drill bit **92** to control the direction of further drilling, and then to drill a short interval and repeat the process. The "away distance" or distance from the well head, or borehole entry point **100** to the drill tool **90** is known. To determine the current location and direction of drilling during the construction of the borehole **80**, the magnetic field produced by the elongated coil assembly **20** is measured by a downhole AC steering tool **102** (**FIG. 7**) that is located in the steering tool package **94**. A suitable steering tool is manufactured by Vector Magnetics, LLC of Ithaca, N.Y. This steering tool incorporates gravity sensors **104**, which are orthogonally related inclinometers for sensing the x, y and z components of gravity, three orthogonally related magnetometers **106** for sensing the x, y and z components of the magnetic field at the location of the tool, and, in a preferred form of the invention, three AC amplifiers **108** for amplifying the x, y and z outputs of the magnetometers **106**. Although a steering tool without AC electromagnetic field amplifiers **108** can be used together with a "reversible" DC current source instead of current source **120**, vastly improved sensitivity results are obtained with the use of the AC method. The inclinometers and the magnetometers measure the vector components of the gravity and of the total magnetic field at the location of the tool along orthogonal x, y and z axes. The z axis is along the tool axis and points along the borehole in the direction of drilling. The y and z axes are perpendicular to the axis of the borehole. Output signals corresponding to the measured AC magnetic field vector components which are produced by the three axis magnetometer are amplified in the instrument package by amplifiers **108**, are supplied to a multiplexer and analog-to-digital converter **110** and are transmitted digitally by way of line **112** uphole to a computer **114** located at the well head of the borehole.

[**0031**] A known current is supplied by an AC source **120** to the coil assembly coils **24** by way of cable **66**, producing a corresponding magnetic field in the earth surrounding the guide borehole **14**. This magnetic field is detected by the magnetometers **106** and a digital stream of AC magnetic field measurements, which are made near the drill bit **92**, is supplied uphole to the computer **114**. The magnetic field measurements are made at a sampling rate greater than the appropriate Nyquist frequency and are transmitted to the computer by way of line **112**. In addition, instantaneous measurements of the current supplied to the elongated coils **24** are supplied to the computer by way of line **122**. In one example of the present invention, the AC source may provide current at a frequency of 3 Hz at an amplitude I, and using typical data analysis, the values of the AC current and the corresponding AC magnetic field amplitudes for each field component are determined.

[**0032**] As illustrated in **FIG. 7**, the AC current source is connected by way of lines **122** and **123** to a reference circuit **124** to produce an output reference signal on line **126** that is in phase with the AC current source **120**. In addition, the AC source output on line **122** is supplied by way of line **127** to a digital data stream circuit **128** and then to a current mixer and low pass filter **130** to produce at **132** a measure of the current I. The output of the multiplexer **110** from the steering tool is supplied by way of line **112** to a demultiplexer which produces signals representing the x, y and z vectors of the earth's field at **134**, and produces signals representing the x, y and z vectors of the earth's gravity at **136**. The digital data stream on line **112**, representing the xyz vectors of the measured AC magnetic field is demodulated at **138** and is supplied through mixer and low pass filter **140** where the measured field is combined with the measured source current to produce magnetic field vectors MHx, MHy, and MHz, as illustrated at **142**. The earth's field measurements at **134** and the gravity measurements at **136** are used to determine, at **144**, the steering tool azimuth, inclination and roll angle. It will be understood that these determinations are implemented by software utilizing standard methods. It is noted that the gravity data sensors **104** directly give the three components of the measured gravity vector MGx, MGy, and MGz at **136**.

[**0033**] An important aspect of the invention is the mathematical method by which the measurements of the gravity vector, MGx, MGy, and MGz, and those of the electromagnetic field, MHx, MHy and MHz, generated by the elongated coil **24** are used to determine the location and direction of drilling. The location coordinates of the drill head **90** and its drilling tool package **94** and the azimuthal direction of the borehole are determined by matching computed electromagnetic field components based on the current supplied to the coil with actual measurements made at package **94**, using the approximation method of Newton Cotes. The theoretical electromagnetic field and the first derivatives of these field values with respect to elevation, right and azimuth of the drilling direction are computed for an assumed, or approximated, tool package location and drilling direction. Values for the parameters of interest, i.e., elevation, right and azimuth of the drilling direction being sought are then systematically adjusted using an iterative procedure to give convergence between the measured values of the fields and the exactly computed theoretical values.

[0034] An appropriate sensing tool coordinate system, in the borehole being drilled, is the gbr system illustrated in **FIG. 8**. This coordinate system is defined by the xyz sensor tool axis coordinate system and by the gravity measurements **104** at the drill head location **90**. Measurements of the AC electromagnetic field components, in the xyz coordinate system of the sensors **106**, are transformed to the gbr coordinate system. These values are equated in order to compute field values to find the parameters of interest.

[0035] References to the coordinate system of the measuring tool, as defined by the sensor axes, are denoted with "xyz". The z-axis points along the tool axis, where a positive value indicates the direction of drilling. The measured values of the electromagnetic field vector MH are denoted by a 3 row, 1 column, i.e., a 3×1 matrix MHxyz of the measured values of MHx, MHy, and MHz. The measured values of the gravity vector MG are denoted by a 3×1 column vector of MGx, MGy, and MGz. Throughout the following discussion, the notation conventions and function designations conform to those defined by the MATLAB language of computing.

[0036] The unit vectors gUv, bhUv, rsUv, which define the gbr coordinate system, are represented in the xyz coordinate system as:

```
gUv=MGxyz/mag(MGxyz);
rsUv=cross(gUv, [001]')/mag(cross(gUv,[001]');
bhUv=cross(gUV,rsUv);
```

[0037] The function "cross" denotes the vector cross product, and "mag" the magnitude of its vector argument. The measured electromagnetic field can be transformed and represented in the gbr system as:

```
MHgbr=[gUv'; rsUv'; bhUv']*MHxyz
```

[0038] The next task is computation of the theoretical electromagnetic field TH at a sensor tool **94** location Rtl, shown diagrammatically in **FIG. 9**, where the field is generated by the N turn, elongated coil **24** carrying an electric current I. The location coordinate system used for the coil and the boreholes is that used by surveyors; i.e., away, elevation and right (aer). The coil **24** can be defined by a matrix tabulation of this aer representation of the coordinates of the Nn nodes defining the coil. Noting **FIG. 9**, a 3×Nn matrix of vectors to the coil nodes is:

```
Rc=[Rn1 Rn2 Rn3 . . . RnNn].
```

[0039] Vectors defining the Nn straight elements connecting the nodes give the 3×Nn matrices of wire segment vectors, and their associated unit vectors are given by:

```
Ws=diff ([Rc Rn1]);
WsUv=Ws./(ones(3,1)*mag(Ws)).
```

[0040] 3×Nn matrices of the vectors Rsttl from the start node of each wire segment to the tool and their unit vectors is are given by:

```
Rsttl=(Rtl*ones(1,Nn))−Rc;
RsftlUv=Rsttl./(ones(3,1)*mag(Rsftl)).
```

[0041] Vectors from the end node of each segment to the tool and their unit vectors are given by:

```
Rendtl=(Rtl*ones(1,Nn))−[Rc(:,2:end) Rc(:,1)];
RendtlUv=Rentl./(ones(3,1)*mag(Rendtl).
```

[0042] The theoretical electromagnetic field, at the tool, in the aer coordinates THaer, is computed using the sequence of computations:

```
Aaer=(cross(WsUv,Rsttl)./(ones3,1)*dot(cross(WsUv,
Rsttl), cross(WsUv,Rsttl));
THaer1=(Nt*l/(4*pi))*Aer.*(ones(3,1)*(dot(RsttlUv,
WsUv)−dot(RendtlUv,WsUv));
THaer=(sum(THaer1')'.
```

[0043] THaer is transformed to the gbr coordinates using the relationship:

```
THgbr=[0−10; cos(Az) 0 sin(Az); −sin(Az) 0 cos(Az)]
*Thaer.
```

[0044] The relationship of the aer coordinate system and the gbr coordinate system is illustrated in **FIG. 10**. The location of the steering tool Rst and the azimuth of direction of drilling; i.e., the angle Az, are found by equating the 3×1 THgbr vector components to the measured MHgbr components.

[0045] The spirit of the analysis is that of the known Newton Cotes method, which starts with an approximate location and borehole direction and slightly changes the parameters being sought until the measured and computed values for the electromagnetic field equal each other.

[0046] Begin by defining a three parameter column vector of elevation, right and Azimuth; ElRghtAz=[El Rght Az]' and the differential parameter vector dElRghtAz=[dEl dRght dAz]. The first approximate value of this vector is defined as ElRghtAz **0**; a neighboring vector is ElRghtAz**1**=ElRghtAz**0**+dElRghtAz. Denote the value of THgbr at ElRghtAz**0** as TH**0** and that at the neighboring point ElRghtAz**1** as TH**1**; the Taylor expansion value of TH**1** is:

```
TH1=TH0+[dTHdEl'; dTHdRght'; dTHdAz']*dEl-
RghtAz
```

[0047] where dTHdEl, dTHRght, dTHdAz are the first derivatives of the column vector THgbr with respect to elevation, right and Azimuth; each derivative is evaluated at the approximate parameter vector ElRghtAz**0**. The computed value TH**1** at the neighboring location is equated to the measured value MHgbr and the resulting equations are solved for the differential parameter vector dEIRghtAz, i.e.:

```
dElRghtAz=[dTHdEl'; dTHdRght'; dTHdAz']\(MH-
gbr−TH0).
```

[0048] An improvement to the approximate value ElRghtAzo for ElRghtAz is given by:

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ElRghtAz1=ElRghtAz0+dElRghtAz
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[0049] This new ElRghtAz1 is used for a new ElrghtAz0 and is iterated to get the solution for the value for the parameter vector ElRghtAz until THgbr=MHgbr with any desired precision.

[0050] The above procedure requires an independent specification of the away distance of the drill bit at the point of the survey. As drilling progresses a new survey is performed as each new section of drill stem **98** is added. Noting the location coordinates of the borehole entry point **100**, and the lengths of drill stem **98** between surveys, the away location for each new survey is readily found using known surveying integration methods, using the previously found elevation and right location parameters along borehole **80**, and using the Az value at the survey location just before that of the new survey being taken.

[0051] The away distance of the drill bit can also be measured directly without depending upon this integration procedure. When it is desired to do so, measurement data from two neighboring drill locations with known borehole lengths between them are used. The method described below works particularly well close to the ends of the coil **24**.

[0052] Computation of the four parameters, Away, Elevation, Right and Azimuth, from electromagnetic measurements is done by fitting a composite data vector from two neighboring locations **1** and **2** at a known borehole distance apart. Put the measurement data MH1gbr and MH2gbr, with known drill stem distance between them, on top of each other to form a 6×1 vector MH12gbr. The theoretical field computation at the approximate locations and azimuths of these two stations gives TH1gbr and TH2gbr. In a similar fashion, stack these two vectors to form a 6×1 TH12gbr**0** column vector. As in the procedure above, the vector TH12gbr is expanded in a Taylor series in the neighborhood of the first guess 4×1 parameter vector AwElRghtAz**0** to give TH12gbr**1**. The error vector dAwElRghtAz is solved for to make TH12gbr**1** equal to the measurement vector MH12gbr as well as possible. The set of 6 linear equations being solved is over-determined; thus, the solution gives a "least squares" fit for each dAwElRghtAz error vector. This is done iteratively, as above, to find all four parameters; i.e., the Away, Elevation, Right coordinates of the tool and the tool Azimuth relative to the Away.

[0053] The method of the present invention operates particularly well where the value of TH12gbr**0** changes significantly as the away parameter of the tool changes. Thus, attempting to determine the Away parameter at points close to the ends of the coil **24**, as compared to the radial distance away and the length of the coil, works well. At the center of the coil, the electromagnetic field does not vary significantly with changes in away distance. The result can be an unstable system of equations that can cause the entire computation to fail. Fortunately, it is easy to test for this condition beforehand by noting the relative value of the derivative of TH12gbr with respect to the away parameter near the first guess value AwElRghtAz**0**.

[0054] In operation, spaced boreholes are accurately drilled along precise paths by first drilling a guide borehole using conventional drilling, surveying and guidance techniques at a drilling site. A coil carrier assembly incorporating plural turns of a coil wrapped longitudinally around an elongated core is inserted in the guide hole. The location and the roll angle of the coil is measured, as by an inclinometer inserted into the core, and the coil is energized by an AC source, preferably operating at a low frequency, to produce a corresponding AC magnetic field that will extend to the region where a second borehole is to be drilled along a specified path. The drilling of the second borehole is guided by periodic measurements of the AC field vectors, the earth's gravity vectors, and the distance of the drill head from the second borehole entry point (the "away" distance) and by iteratively calculating the theoretical location of the drill head and comparing these calculations with the measurements of its actual location. When these values match, the location of the drill head with respect to the borehole is known, and the direction of further drilling is determined. This process is repeated periodically to produce a second borehole that follows a selected path with respect to the known path of the guide borehole. Multiple boreholes may be drilled at spaced locations from the guide borehole.

[0055] While the invention is described herein with reference to illustrative embodiments for particular applications, it should be understood that the invention is not limited thereto. Those having ordinary skill in the art and access to the teachings provided herein will recognize additional modifications, applications and embodiments with the scope thereof and additional fields in which the present invention would be of significant utility.

What is claimed is:

1. Apparatus for guiding the drilling of a borehole in the earth in spaced relationship to a guide borehole in the earth, comprising:

a coil assembly incorporating an elongated core carrying a longitudinal coil winding located in the guide borehole;

a source of current connected to said coil to produce a magnetic field in the earth surrounding the guide borehole and in the region of the borehole being drilled;

sensors in said borehole being drilled for detecting vectors of gravity and of the generated magnetic field; and

a controller responsive to the generated magnetic field and the measured magnetic field vectors to control the direction of further drilling.

2. The apparatus of claim 1, where the coil assembly core is generally tubular with a longitudinal axis and incorporates diametrically opposite external ridges parallel to said axis for receiving and positioning said coil winding.

3. The apparatus of claim 2, wherein said coil includes multiple windings positioned by said ridges to lie in a plane that includes said axis.

4. The apparatus of claim 3, wherein said coil passes around a first, distal end of said core, and passes over the exterior of said core to cause the second, near end of the core to extend out of the coil.

5. The apparatus of claim 4, wherein said near end of said core is extendable to permit said coil to be positioned at any location in said guide borehole.

6. The apparatus of claim 5, wherein said core includes internal grooves for receiving and guiding instrumentation along the length of the core.

7. The apparatus of claim 6, wherein said instrumentation includes an inclinometer for measuring the roll angle of said coil.

8. The apparatus of claim 7, wherein said instrumentation is a survey instrument for surveying said guide borehole.

9. The apparatus of claim 5, further including spaced straps for securing said coil winding on said core.

10. The apparatus of claim 4, further including a cable connected to said winding for connecting said winding to said source of alternating current.

11. The apparatus of claim 10, wherein said controller includes a computer for iteratively calculating theoretical magnetic fields produced by said coil and comparing the theoretical fields with magnetic fields measured by said sensors for determining the location of said sensors with respect to said coil.

12. A method for controlling the drilling of a borehole with respect to a guide borehole, comprising:

drilling a guide borehole;

obtaining a survey of said guide borehole to determine its path;

inserting in said guide borehole a coil assembly including a tubular, nonmagnetic core and at least one winding wound externally on said core in a plane parallel to the longitudinal axis of the core;

energizing said core with an excitation current to produce a corresponding magnetic field;

partially drilling with a drilling tool a second borehole near said guide borehole;

detecting the produced magnetic field at the drill head of the drilling tool;

iteratively comparing the detected magnetic field with theoretical magnetic fields calculated from said current and the location of said coil assembly to determine the location of the drill head with respect to said coil assembly; and

guiding the further drilling of said second borehole in accordance with the calculated location of the drill head.

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