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(54) Title: APPARATUS TO MEASURE THE EARTH'S LOCAL GRAVITY AND MAGNETIC FIELD IN CONJUNCTION WITH GLOBAL POSITIONING ATTITUDE DETERMINATION

(57) Abstract: The present invention provides a method for determining magnetometer errors during wellbore survey operations. It is capable of determining errors on up to three axes, with or without the use of an external reference measurement of the local magnetic field, and is capable of providing an accurate result using data from a minimum number of surveys. A model is used to correct the observed data and the corrected data are transformed from the tool coordinate system to a different coordinate system referenced to the earth. The difference between the corrected transformed data and reference data in the earth coordinate system is minimized to determine the model parameters. The present invention also provides a method for determining residual uncertainty in the measurements and for quality control of the measurements. Once a survey has been obtained with reference to magnetic north, it is corrected using magnetic declination data obtained concurrently with the survey using surface GPS receivers, magnetometers and accelerometers.

APPARATUS TO MEASURE THE EARTH'S LOCAL GRAVITY AND MAGNETIC FIELD IN CONJUNCTION WITH GLOBAL POSITIONING ATTITUDE DETERMINATION

5   BACKGROUND OF THE INVENTION

1.   **Field of the Invention:**

The present invention is related to the field of surveying of wellbores. Specifically,

10   the present invention uses 3-component magnetometer and accelerometer data downhole to

determine an azimuth of the borehole relative to magnetic north and then uses a determination

of magnetic declination using Global Positioning Satellite (GPS) data to obtain an azimuth

relative to true north.

2.   **Description of the Prior Art:**

15   Surveying of wellbore orientation is commonly performed by the use of instruments

containing sets of three orthogonal axes accelerometers and magnetometers, which are

inserted within the drillstring and used to measure the orientations of the local gravitational

and magnetic field vectors. In order to measure the earth's magnetic field, which is used as a

north reference from which wellbore azimuth may be computed, the instruments must be

20   placed within a section of non-magnetic material extending between upper and lower

ferromagnetic drillstring sections. These ferromagnetic portions of the drillstring tend to

acquire magnetization as they are repeatedly strained in the earth's magnetic field during

drilling operations. The nominally non-magnetic portion of the drillstring may also acquire

some lesser magnetization as a result of imperfections. The result is that magnetometer

25   measurements made by an instrument within a drillstring may measure not the undisturbed

magnetic field, but the vector sum of the earth's field and an error field caused by drillstring

magnetization. Since the tool is fixed with respect to the drillstring, the error field is fixed

with respect to the tool's coordinate system and it appears as bias errors on the magnetometer

measurements, which can lead to errors in the determination of wellbore azimuth and

trajectory unless measures are taken to compensate for these bias errors.

Since the greater part of the drillstring magnetization occurs in the ferromagnetic portions of the drillstring, which are displaced axially from the instrument, the bias error in the axial direction usually exceeds the transverse bias errors. Various methods have therefore been published which seek to determine axial magnetometer bias errors in a single directional survey, including U.S. Pat. Nos. 3,791,043 to *Russell*, 4,163,324 to *Russell*, Re. 33,708 to *Roesler*, 4,761,889 to *Cobern*, 4,819,336 to *Russell*, 4,999,920 to *Russell*, and 5,155,916 to *Engebretson*. All of these methods require the provision of an independent estimate of one or more components of the earth's magnetic field, and as a result all of them tend to lose accuracy in those attitudes in which the direction of the independent estimate is perpendicular to the drillstring and therefore contributes little or no axial information. In particular, all of these methods lose accuracy as the wellbore attitude approaches horizontal east-west. A number of methods have also been published which seek to determine magnetometer biases on all three axes, including U.S. Pat. Nos. 4,682,421 to van *Dongen* and 4,956,921 to *Coles*, and UK Pat. No. 2,256,492 to *Nicolle*. While certain of these methods can resolve transverse bias components without external estimates of the field, they all require an independent estimate of the earth's magnetic field in order to determine the axial bias component, and therefore they also tend to lose accuracy as the attitude approaches horizontal east-west. U.S. Pat. No. 4,709,486 to Walters discloses a method for determining axial bias errors without any external estimate, by the simultaneous use of transverse magnetometer data from a plurality of surveys. However the method fails to make use of the valuable information contained in the axial magnetometer measurements, since it does not require any correlation between the axial biases determined at the plurality of attitudes. In U.S. Pat. No. 5,321,893, Engebretson discloses a method which may be used to determine magnetometer scale factor and bias errors from a plurality of surveys with or without requiring any external estimate of the earth's field. However, the method is inherently approximate since it requires the construction of a "measurement matrix", whose elements depend on the unknown borehole attitude and

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magnetic dip angle. U.S. Pat. No. 5,623,407 to the present inventor and having the same

assignee discloses a method for determining magnetometer biases during wellbore survey

operations, which is capable of determining biases on up to three axes, with or without the use

of an external estimate of the local magnetic field, and which is capable of providing an

5   accurate result using data from a minimum number of surveys. Also disclosed in U.S. Pat.

No. 5,623,407 is a method for determining magnetometer biases which may vary between

surveys in a predefined manner. What is lacking in prior art is the ability to deal with biases

in the accelerometers and properly correcting for them, the ability to estimate the uncertainty

of corrected measurements and the ability to acquire and use locally measured reference

10   values of the earth's magnetic field..

Additional objectives, features and advantages of the present invention will be

apparent in the written description which follows.

15   **SUMMARY OF THE INVENTION**

The present invention provides a method for determining magnetometer errors during

wellbore survey operations and referencing the corrected azimuth measurements to true north.

It is capable of determining errors on up to three axes, with or without the use of an external

reference measurement of the local magnetic field, and is capable of providing an accurate

20   result using data from a minimum number of surveys. A model is used to correct the observed

data and the corrected data are transformed from the tool coordinate system to a different

coordinate system referenced to the earth. The difference between the corrected transformed

data and reference data in the earth coordinate system is minimized to determine the model

parameters. The present invention also provides a method for determining residual uncertainty

25   in the measurements and for quality control of the measurements. By making the observations

over a period of time, any deterioration of the sensors may be identified. When combined

with a determination of magnetic declination using GPS data, a more accurate survey of a

borehole relative to true north is obtained.

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BRIEF DESCRIPTION OF THE DRAWINGS

The novel features believed characteristic of the invention are set forth in the

5   appended claims. The invention itself, however, as well as a preferred mode of use, further

objectives and advantages thereof, will best be understood by reference to the following

detailed description of an illustrative embodiment when read in conjunction with the

accompanying drawings, wherein:

Figure 1 shows a typical drilling operation comprising a drilling rig, a drillstring

10   including a survey instrument, and a fluid circulating system;

Figure 2 shows a typical tool-fixed coordinate system used by a magnetic survey

instrument located within a drillstring;

15   **Figure 3** (PRIOR ART) shows the application of conventional methods for the

correction of bias errors based upon external field measurements;

Figure 4 shows the application of the present invention for correction of errors in

multiple surveys;

20

Figure 5 shows a schematic view of an apparatus for determination of magnetic

declination using GPS data.

DETAILED DESCRIPTION OF THE INVENTION

25   **Figure 1** illustrates a rig engaged in drilling operations; the equipment includes a

derrick **1**, drawworks **2**, cable **3**, crown block **4**, traveling block **5**, and hook **6**, supporting a

drillstring which includes a swivel joint **7**, kelly **8**, drillpipe **9**, drill collars **10**, and drill bit **11**.

Pumps **12** circulate drilling fluid through a standpipe **13** and flexible hose **14**, down through

the hollow drillstring and back to the surface through the annular space **15** between the

drillstring and the borehole wall **16**. During the course of drilling a borehole for oil or gas

exploration, it is advantageous to measure from time to time the orientation of the borehole in

order to determine its trajectory. This can be accomplished by the use of a survey tool **17**

5   located within the drill collars **10**, for measuring the direction and magnitude of the local

gravitational and magnetic fields with respect to a tool-fixed coordinate system. It is

customary to take one survey each time the drilling operation is interrupted to add a new

section to the drillstring; however, surveys can be taken at any time.

10   Still referring again to **Figure 1**, the measured data are transmitted to the surface by

modulating a valve (not shown) placed in the flow passage within or adjacent to survey tool

17, causing pressure pulses to propagate in the mud column up the drillstring, where they are

detected by a pressure transducer **18** placed in the standpipe **13** and communicated to data

processing system **24** which may be located on the rig floor or in a logging trailer or other

15   work area, which is approximately programmed to (1) to interpret the pressure pulses (2)

eliminate the influence of magnetic field bias error components and (3) calculate one or more

conventional wellbore orientation indicators. Data processing system **24** may be programmed

in accordance with the present invention. Other methods and devices for communicating data

uphole, such as electromagnetic methods or acoustic signals in the drillstring, could also be

20   used and are intended to be within the scope of the invention.

The borehole inclination can be determined by use of the gravitational measurements

alone, while the borehole azimuth is determined from the gravitational and magnetic

measurements; since the azimuth uses the direction of the local magnetic field as a north

reference, it is necessary for the survey tool **17** to be placed in non-magnetic portions **19** and

25   **20** of the drillstring situated between upper and lower ferromagnetic sections **21** and **22**.

Magnetization of the upper and lower ferromagnetic sections **21** and **22**, as well as

imperfections in the non-magnetic materials comprising the survey tool **17** and the non-

magnetic collars **19** and **20** can produce a magnetic error field, which is fixed in the tool's

frame of reference and which therefore appears as bias errors affecting the magnetic

measurements. The present invention is directed to determining these errors in order to

compensate for their presence and thus to provide more accurate measurements of borehole

azimuth.

The invention will first be described as it pertains to solving for constant bias errors

along each axis. It is conventional to define the tool-fixed coordinates as x, y and z, the z-

coordinate being aligned with the drillstring axis as illustrated in **Figure 2**. The instrument

measures three components Gx, Gy and Gz of the gravitational vector **G**, and three

components Bx, By and Bz of the magnetic flux density vector **B**.

The principal sources of azimuth uncertainty in magnetic surveys are sensor errors,

uncertainty in the magnetic declination, instrument misalignment, and drillstring

magnetization. The overall uncertainty at a bottomhole location tends to be dominated by the

declination and magnetization errors, since these are systematic over a group of surveys.

Arrays of accelerometers and magnetometers respectively measure the direction of the gravity

and magnetic field vectors with respect to the tools *x-y-z* coordinate frame. The azimuth is

then computed as

$$A = \arctan\left[\frac{\left(G_x^2 + G_y^2 + G_z^2\right)^{0.5} \cdot \left(B_y G_x - B_x G_y\right)}{B_z \cdot \left(G_x^2 + G_y^2\right) - G_z \cdot \left(B_x G_x + B_y G_y\right)}\right]$$

(1)

Accelerometer and magnetometer sensor errors $_{,g}$ and $_{,b}$ cause the measurements to be

imprecise, and the consequent uncertainties in azimuth may be estimated as

$$\delta Ag = \varepsilon_g \cdot \left[\left(\frac{\partial A}{\partial G_x} \right)^2 + \left(\frac{\partial A}{\partial G_y} \right)^2 + \left(\frac{\partial A}{\partial G_z} \right)^2 \right]^{0.5} \qquad ($$

$$= \frac{180}{\pi} \cdot \frac{\varepsilon_g}{G} \left[\frac{B_v^2}{B_h^2} + \frac{1}{\tan^2 I} - 2 \frac{B_v \cos A}{B_h \tan I} \right]^{0.5}$$

(2) and

$$\delta Ab = \varepsilon_b \cdot \left[\left(\frac{\partial A}{\partial B_x} \right)^2 + \left(\frac{\partial A}{\partial B_y} \right)^2 + \left(\frac{\partial A}{\partial B_z} \right)^2 \right]^{0.5} = \frac{180}{\pi} \cdot \frac{\varepsilon_b}{B_h} \qquad (3)$$

where B_h and B_v are the horizontal and vertical components of the local magnetic flux density,

and I is the inclination.

The accelerometer and magnetometer errors are uncorrelated, thus the overall

azimuth uncertainty due to sensor errors is

$$\delta A = \left(\delta A_g^2 + \delta A_b^2 \right)^{0.5}$$

(4)

The azimuth determined by such a survey is relative to magnetic north and in order to

obtain a correct survey, the magnetic declination at the time of the survey must be known.

Incorrect declination values are a primary source of azimuth error in magnetic surveys. One

method of avoiding large declination errors is a site survey and in-field referencing to provide

local magnetic field parameters in real time. In the present invention, such a site survey is

obtained using the method described in United States Patent Application Ser. No. 09/309,864

filed on May 11, 1999, now United States Patent 6,212,476 the contents of which are fully

incorporated herein by reference and are discussed below in reference to **Fig. 5.**

5   Another source of errors in survey tools is misalignment of the tool's axis with the

borehole, however these azimuth errors are usually small in comparison with the others and

their effect tends to be randomized as the toolface angle changes between surveys.

          Yet another source of errors arises from the fact that as magnetic drillstring materials

10   are rotated and stressed in the earth's magnetic field, they may develop permanent

magnetization. Some components may be magnetized further during inspection and

transportation. Magnetic poles are produced close to the ends of each member of the

drillstring, although some components may also develop intermediate poles. Each pole

produces an error field at the sensor proportional to its pole strength and inversely

15   proportional to the square of its distance from the sensor. The error field seen by the sensor is

assumed to be the sum of the contributions from all the poles.

          Since magnetic drillstring components are normally spaced at least several meters

axially from the sensors, the error fields due to permanent magnetization tend to be closely

20   aligned with the z-axis. The error field therefore appears equivalent to a bias error on the z-

magnetometer. A cross-axial bias effect may also be present as a result of off-axis magnetic

poles, drillstring bending, or hot spots in nonmagnetic collars, but the cross-axial effect is

typically an order of magnitude smaller than axial.

25   Magnetic drillstring components may exhibit both remanent and induced

magnetization. The error field due to induced magnetization is caused by magnetic poles

where the flux enters or leaves the more permeable materials; it is proportional to the

magnitude of the external field and therefore it appears similar to a magnetometer scale factor

error. The induced error field is not necessarily parallel to the external field, thus the apparent

scale factor errors may differ among the three magnetometer axes. Experiments have shown

that the induced axial magnetization associated with drillstring components is usually small in

comparison with the remanent component, and its effect may sometimes be masked by

5   downhole changes in remanent magnetization over a period of time. The error field due to

induced magnetization is particularly small near the important horizontal east-west attitudes,

as the axial component of the external field then approaches zero.

Conventional magnetic corrections process each survey independently, by assuming

10   the error field to be aligned with the z-axis. The unknown z-component of the flux density

leaves a single degree of freedom between the components of the local field.

A prior art method is illustrated schematically in **Fig. 3.** The abscissa **101** is the

horizontal component of the magnetic field and the ordinate **103** is the vertical component of

15   the magnetic field. Different points along the curve **105** correspond to different biases in the

z-component of the gravity measurement and corresponding values of the apparent azimuth of

the tool. The equations relating the gravity measurements to the magnetometer measurements

are:

$$G_{meas} = (Gx_{meas}^2 + Gy_{meas}^2 + Gz_{meas}^2)^{0.5}$$

20         $$B_{meas} = (Bx_{meas}^2 + By_{meas}^2 + Bz_{meas}^2)^{0.5}$$

$$Bv_{meas} = (Bx_{meas} Gx_{meas} + By_{meas} Gy_{meas} + Bz_{meas} Gz_{meas}) / G_{meas}$$

$$Bh_{meas} = (B_{meas}^2 - Bv_{meas}^2)^{0.5} \hspace{4cm} (5)$$

The point **107** represents an externally supplied reference field measurement. Methods for

25   obtaining this reference measurements are discussed below. In prior art, the solution is taken

as the point **109** on the curve which minimizes the vector distance to the externally-supplied

reference field. This point is obtained by dropping a perpendicular from 107 to the curve.

The major problem with prior art corrections of this type is that their accuracy

degrades in horizontal boreholes having an east-west orientation. These attitudes are,

unfortunately, those in which the drillstring magnetization effects tend to reach a maximum.

5   The present invention uses data from a number of surveys and explicitly assumes that

error components are common to all surveys. Based on this assumption, the variance among

apparent local field values is minimized. For example, if a common axial magnetic error

component is estimated as a bias $_{,bz}$, the z-magnetometer measurement of the n-th survey can

be corrected by

10

$$Bz_{corr_n} = Bz_{meas_n} - \varepsilon_{bz}$$

The vertical and horizontal components of the local magnetic flux density can then be

computed by

15

$$Bv_n = \frac{\left(Bx_n \cdot Gx_n + By_n \cdot Gy_n + Bz_{corr_n} \cdot Gz_n\right)}{\left(Gx_x^2 + Gy_y^2 + Gz_z^2\right)^{0.5}}$$

(7)

20   and

$$Bh_n = \left(Bx_x^2 + By_y^2 + Bz_{corr_n}^2 - Bv_n^2\right)^{0.5}$$

(8)

Bv_n and Bh_n are thus measurements that have been corrected and transformed from

the tool coordinate system (x,y,z) to horizontal and vertical coordinates, i.e., an earth-

25   referenced coordinate system. The variance in the corrected transformed measurements over

N surveys with respect to reference vertical and horizontal measurements Bv_{ref} and Bh_{ref} is

thus   (9)

$$V = \frac{1}{N-1} \sum_{n=1}^{N} \left[\left(Bh_n - Bh_{ref}\right)^2 + \left(Bv_n - Bv_{ref}\right)^2\right]$$

Those versed in the art would recognize that instead of horizontal and vertical reference data, the reference data could be in any other set of coordinates. Such variations are intended to be within the scope of the invention.

5   In one embodiment of the invention, the reference values are obtained using the method and apparatus described below with reference to **Fig. 5**. The advantage of such a referencing method is that local reference values may be obtained while the survey is being carried out. This avoids errors that would occur if the reference values are obtained from published tables that do not take into account temporal variations of the earth's magnetic field.

10   With such a method, **eq. (8)** gives a straightforward nonlinear minimization problem that may be solved using known methods.

Another embodiment of the present invention using multiple surveys is illustrated in **Fig. 4**, where three surveys are shown, depicted by **123, 125** and **127**. The raw data are indicated by the points **123a, 125a** and **127a**. The data corresponding to one trial value of the

15   z- magnetometer bias $_{,bz}$ are denoted by **123b, 125b** and **127b**, Correction with a second trial value of the z- magnetometer bias $_{,bz}$ are denoted by **123c, 125c** and **127c** while correction with a third trial value of the magnetometer bias gives the points **123d, 125d** and **127d**. In this example, the points are grouped most closely about the reference value **107** and the variance is minimized by using trial value 3 (corresponding to zone **135**). A bias value close

20   to this is selected as the optimum and the surveys are corrected accordingly.

Since the variance V is nonlinear with respect to $_{,bz}$, it is minimized by setting (MV / M$_{,bz}$) to zero, using an iterative technique such as Newton's method, in which successive approximations to $_{,bz}$ are obtained by

25   (10)

$$\varepsilon_{bz} = \varepsilon_{bz} - \frac{\left(\dfrac{\partial V}{\partial e_{bz}}\right)}{\left(\dfrac{\partial V^2}{\partial e_{bz}^2}\right)}$$

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After the iterative process converges to a solution, the residual value of V may be used as a quality indicator and as an input quantity for the calculation of residual uncertainty.

This invention is not limited to solving for a single unknown $_{,bz.}$ It can be extended to solve for any number of unknown parameters, limited only by the number of surveys. The m unknowns are expressed as a vector U, then the solution is obtained by iteration:

$$U = U - \left(\frac{\partial^2 V}{\partial u^2}\right)^{-1} \left(\frac{\partial V}{\partial U}\right)$$

(11)

where (MV/MU) is a vector of length m, and (M^2V/MU^2) is a $m \times m$ matrix. This is done in the preferred embodiment of the intention.

In one embodiment of the invention, the unknown vector U can contain coefficients applicable to each of the three sensor axes. The unknowns may include not only the magnetometer coefficients, but also accelerometer parameters. In this case, the expression for V is of the form

$$V = \frac{1}{N-1} \sum_{n=1}^{N} \left[\left(Bh_n - Bh_{ref}\right)^2 + \left(Bv_n - Bv_{ref}\right)^2 \right] + \frac{1}{N-1} \sum_{n=1}^{N} W^2 \left(G_n - G_{ref}\right)^2$$

(12)

where W is a weighting factor relating the measurement units and the residual uncertainties in the G and B fields. The same method may be used for determining biases, scale factors, and misalignments from data obtained during total field calibrations in the laboratory. Since the errors in the magnetic field have no effect on the accelerometer measurements, an alternate embodiment of the invention solves for the accelerometer term alone, i.e., minimizing **eq. (12)** with W having a very large value, and then repeating the minimization using values of the accelerometer parameters to find the magnetometer parameters that minimize **eq. (9)**.

Coefficients for computing reference magnetic field values for use in **eqs. (9)** and **(12)** are

regularly published by agencies such as the British Geologic Survey or obtained as discussed

below with reference to **Fig. 5**.

5   Another embodiment of the invention can be used where there is no independent

estimate of the reference field. The reference values in **eqs. (9)** and **(12)** for variance are

replaced by mean values. After making the computation, the mean field components provide

an estimate of the local field without the need for any external information.

10   Another embodiment of the invention uses in-field referencing (IFR) or interpolation

in-field referencing (IIFR); As would be known to those versed in the art, IFR provides an

onsite monitoring of the local magnetic field of the earth and IIFR makes use of monitoring of

the magnetic field of the earth at a location away from the wellsite in combination with a

single onsite survey. This embodiment makes use of updated three-component reference field

15   values for each survey. Substantial improvement in survey quality is obtained when the

correction is combined with IFR or IIFR. By addressing both drillstring interference and

declination uncertainty, the two largest contributors to azimuth uncertainty have been reduced.

The present invention obtains an IFR using GPS measurements as described below with

reference to **Fig. 5.**

20

For subsurface anomalies, or for IIFR applications without a site survey, the present

invention can calculate two components of the local flux density, although not the declination.

Offsets are added to the reference components in the variance expression, and they are solved

as additional elements of the unknown vector **U**. Specifically, these may be a bias term in the

25   reference field and a bias term in the dip angle. In the case where all three magnetometer

scale factor errors are unknowns, a local dip offset can still be determined, although the

reference total flux density must then be accepted from an external source. This mode of

operation is limited by the assumption that the anomalies are the same for all surveys

processed as a group.

Since the computation can identify and correct most of the systematic errors common
to all surveys in the set, the residual errors are modeled as random errors or sensor noise. The
magnitude of the noise can be estimated from sensor specifications and knowledge of the local
field, or it can be estimated more directly from the residual variance V observed in total flux
density. The square root of V may be used to approximate the standard deviation Φ of the
noise on each magnetometer channel. For a three-axis correction, the effect on the solution
vector of this level of noise is approximated by the covariance matrix

$$C = \sum_{i=1}^{3} \sum_{j=1}^{N} (U_{ij} - U)(U_{ij} - U)^{T}$$

(13)

where ^{T} denotes the transpose of a matrix. In **eq. (13)**, $\mathbf{U}_{ij}$ is the solution obtained when the 1-
Φ noise perturbation was applied to the i-th magnetometer channel for the j-th survey, and $\mathbf{U}$
is the unperturbed solution. The index i in **eq. (12)** corresponds to the three coordinate axes of
the tool while the index j corresponds to the number of surveys. Elements of the normalized
covariance matrix $(\mathbf{C}/V)$ can be used to indicate matrix condition and stability of the solution.
The effect on azimuth at each survey station can be expressed at one standard deviation by

$$\delta A = \sum_{i=1}^{3} \sum_{j=1}^{N} [(A_{ij} - A)^{2}]^{0.5}$$

(14)

where A_{ij} is the azimuth value at that station computed using sensor measurements adjusted by
the coefficient vector $\mathbf{U}_{ij}$, and A is the azimuth corresponding to $\mathbf{U}$.

Similarly, the uncertainty in the borehole position may be estimated by

$$C = \sum_{i=1}^{3} \sum_{j=1}^{N} (r_{ij} - r)(r_{ij} - r)^{T}$$

where r_{ij} is the position vector with components (north, east, vertical) determined using

perturbed measurements, and r is the unperturbed value of the position vector.

The result of using the method illustrated in **Fig. 4** is an estimate of the tool azimuth

5   referenced to magnetic north (from solution of **eq. 11**) and its inclination. In order to obtain a

survey referenced to true north, the magnetic declination at the time of the survey must be

known. The method of obtaining the magnetic declination is next discussed with reference to

Fig. 5.

10   The main component parts of the method for determination of magnetic declination

are illustrated in **Fig. 5**. A drilling rig **210** is shown on the surface of the earth **205**. At a

distance **d** from the drilling rig, a stable platform **220** is located, the platform having a

longitudinal axis generally indicated by **221**. The distance **d** is typically between 100 and 200

feet. The platform is made of a non-magnetic material, such as fiberglass, to avoid the

15   introduction of any local magnetic perturbations.

Also located on the platform are at least two GPS receivers, indicated here by **222a**

and **222b**. In the illustration, without limitation, they are shown as being positioned along the

longitudinal axis of the platform. Those versed in the art would recognize that as long as the

20   two GPS receivers **222a** and **222b** are on a line whose orientation to the longitudinal axis of

the platform is known, the invention as described below would still function.

Located on the surface of the platform is a 3-component magnetometer, indicated

here by **224**. For purposes of illustration, the three components (m_z, m_y and m_x) of the

25   magnetic field of the earth measured by the magnetometer **224** are indicated by arrows as

being perpendicular to the surface of the platform, along the longitudinal axis of the platform

and at right angles to the longitudinal axis of the platform. These three components are

orthogonal to each other. Also located on the surface of the platform is a 3-component

accelerometer **226** that measures the components of gravity g_x, g_y and g_z in the x, y, and z directions.

A processor **230** that may be located on or in the vicinity of the platform, receives

5   signals from the GPS receivers **222a** and **222b**, the magnetometer **224** and the accelerometer

226. The signals may be transmitted by any suitable telemetry means, including wires, fiber

optics or by radio transmission. The method of determining the attitude of the GPS receivers

with respect to each other is based upon the NAVSTAR GPS based Attitude Determination

System incorporated in a product sold under the mark STINGRAY® by Collins Avionics and

10   Communications Division of Rockwell. A summary of the technique used to determine the

attitude of the two GPS receivers is given here.

The present invention also includes three single component magnetometers labeled

228a, **228b** and **228c** that are at locations displaced in the y, z and x directions from the

15   magnetometer **226**. Differences between values measured by these three single component

magnetometers and the corresponding components measured by magnetometer **226** gives a

measurement of the local magnetic field gradient. This serves as a quality control

measurement. For example, a bucket of nails placed near the platform inadvertently will

provide a large change in the magnetic gradient that is easily detectable and appropriate

20   remedial steps can be taken.

As described in the '864 application (now US Patent 6,212,476), the use of the GPS

sensors in conjunction with the accelerometers makes it possible to determine the azimuth

(yaw) as well as the roll and tilt angle of the platform. When combined with the

25   magnetometer measurements, the magnetic declination may be determined. Thus, using the

determined magnetic declination (something that is done in real time in conjunction with the

downhole survey) makes it possible to reference the survey data obtained from the method

described in **Fig. 4** to true north.

Additionally, the magnetometer data from the surface equipment also provides

reference measurements (such as total field and dip angle) that may be used in the

minimization of **eq. 9** as discussed above, to give downhole magnetometer measurements

5   corrected for magnetometer bias.

As in prior art, the present invention includes the capability for transmitting

measurements to the earth's surface utilizing measurement-while-drilling (MWD)

transmission techniques. These data may be used by a processor **24** that is preprogrammed in

10   accordance with the methods discussed above. The program includes as inputs the x-, y- *and*

z- components of the local magnetic and gravitational fields at each survey station. The

calculations are performed in accordance with the description above, and the processor

provides as an output for each survey station the wellbore azimuth and inclination. In an

alternate embodiment of the invention, the processor may be downhole, and reference field

15   measurements may be transmitted downhole to the processor.

The present intention is illustrated by way of the foregoing description, and various

modifications will be apparent to those skilled in the art. It is intended that all such variations

be within the scope and spirit of the appended claims.

CLAIMS

What is claimed is:

1   1.   A method of obtaining a survey of a wellbore during drilling of a wellbore, comprising:

2   (a)   obtaining a plurality of magnetic and gravitational measurements at selected

3   locations in said wellbore;

4   (b)   using a model comprising a set of model parameters for correcting values of said

5   plurality of magnetic and gravitational measurements for producing a plurality of

6   corrected magnetic and gravitational measurements;

7   (c)   performing a coordinate transformation of the plurality of corrected magnetic and

8   gravitational measurements to give a plurality of transformed corrected magnetic and

9   gravitational measurements;

10   (d)   defining a measure of a difference between the plurality of transformed corrected

11   measurements and reference values of magnetic and gravitational measurements;

12   (e)   determining values for the set of model parameters that minimize the measure of

13   difference, giving a survey of the wellbore referenced to magnetic north;

14   (f)   obtaining estimates of magnetic declination corresponding to said plurality of

15   magnetic and gravitational measurements in said wellbore; and

16   (g)   correcting said survey to true north using said estimates of magnetic declination.

1   2.   The method of claim 1 further comprising determining the accuracy of one or more of the

2   plurality of magnetic and gravitational measurements using the model.

1   3.   The method of claim 2 wherein determining the accuracy of one or more of the plurality of

2   magnetic or gravitational measurements further comprises determining the minimum value of

3   said measure of difference.

1   4.   The method of claim 1 wherein the model includes one or more parameters selected from (i) a

2   bias in at least one component of the gravity measurements, (ii) a bias in at least one

3   component of the magnetic measurements, (iii) a scale factor for at least one component of the

4   gravity measurements, (iv) a scale factor for at least one component of the magnetic

5   measurement, (v) a misalignment of at least one sensor making the gravity measurements, and

6   (vi) a misalignment of at least one sensor making the magnetic measurements.

1   5.   The method of claim 1 wherein determining the model parameter includes one or more

2   parameters selected from (i) a bias in at least one component of the gravity measurements, (ii)

3   a scale factor for at least one component of the gravity measurements, and, (iii) a

4   misalignment of a sensor used to make the gravity measurements, to give a subset of

5   determined model parameters, the method further comprising using the subset of determined

6   model parameters to obtain additional model parameters selected from (A) a bias for at least

7   one component of the magnetic measurements(B) a scale factor for at least one of the

8   magnetic measurements, and (C) a misalignment of at least one sensor used for making the

9   magnetic measurements.

1   6.   The method of claim 1 further comprising providing an onsite monitoring of the local

2   magnetic field of the earth to give said reference values.

1   7.   The method of claim 1 further comprising monitoring the magnetic field of the earth at a

2   location away from the wellsite to give said reference values.

1   8.   The method of claim 1 wherein said reference values further comprise at least one

2   independent measurement selected from (i) a component of the gravitational field, and (ii) a

3   component of the magnetic field.

1   9.   The method of claim 1 wherein said reference values are averages of said plurality of said

2   transformed corrected measurements.

1   10.   The method of claim 1 further comprising determining a variation in the values for

2   the set of model parameters over a period of time to determine any deterioration in

3   sensors making the plurality of measurements.

4   11.   The method of claim 1 wherein the plurality of magnetic and gravitational

5   measurements are sent by telemetry to a surface processor and the surface processor

6   is adapted to perform steps (b), (c) , (d) and (e).

7   12.   The method of claim 1 wherein obtaining estimates of the magnetic declination

8   further comprises:

9   (i)   placing at least two Global Positioning Sensor (GPS) receivers, an

10   accelerometer and a 3-component magnetometer on a non-magnetic

11   platform near said wellbore, said at least two GPS receivers spaced apart

12   from each other;

13   (ii)   receiving electromagnetic signals from a plurality of satellites at the at least

14   two GPS receivers;

15   (iii) providing signals indicative of the position of the at least two GPS

16   receivers to a processor;

17   (iv)   measuring three independent components of the earth's magnetic field with

18   the 3-component magnetometer and providing signals indicative thereof to

19   the processor;

20   (v)   measuring three independent components of acceleration using the

21   accelerometer and providing signals indicative thereof to the processor; and

22   (vi)   using the processor to process the signals from the at least two GPS

23   receivers, the accelerometer and the 3-component magnetometer to

24   determine the magnetic declination.

25   13.   The method of claim 12 wherein said platform is a fixed platform and said

26   accelerometer comprises a two component accelerometer.

27   14.   The method of claim 12 wherein said accelerometer comprises a three component

28   accelerometer.

15. The method of claim 12 further comprising:

A. using a proton magnetometer for measurement of the total magnetic intensity of the earth's magnetic field and providing a signal indicative thereof to said processor; and

B. including the signal from the proton magnetometer in the processing of signals by the processor to determine the magnetic declination.

16. The method of claim 12 wherein using the processor further comprises:

A. determining a yaw angle from the signals from the at least two GPS receivers and the accelerometer;

B. determining a magnetic north direction from the signals from the 3-component magnetometer and the 3-component accelerometer; and

C. determining the magnetic declination from the results of (i) and (ii).
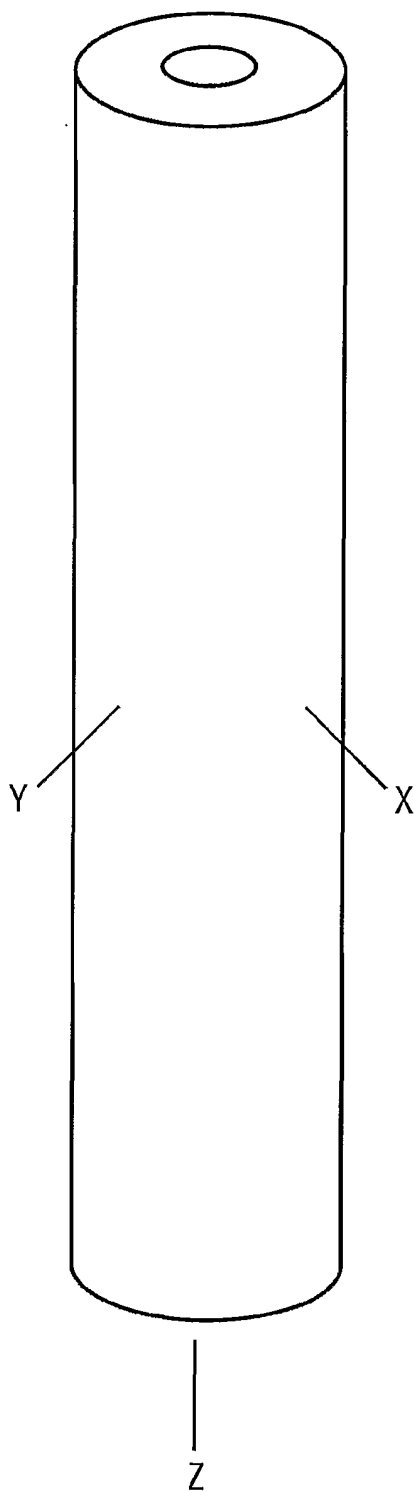
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FIG. 1

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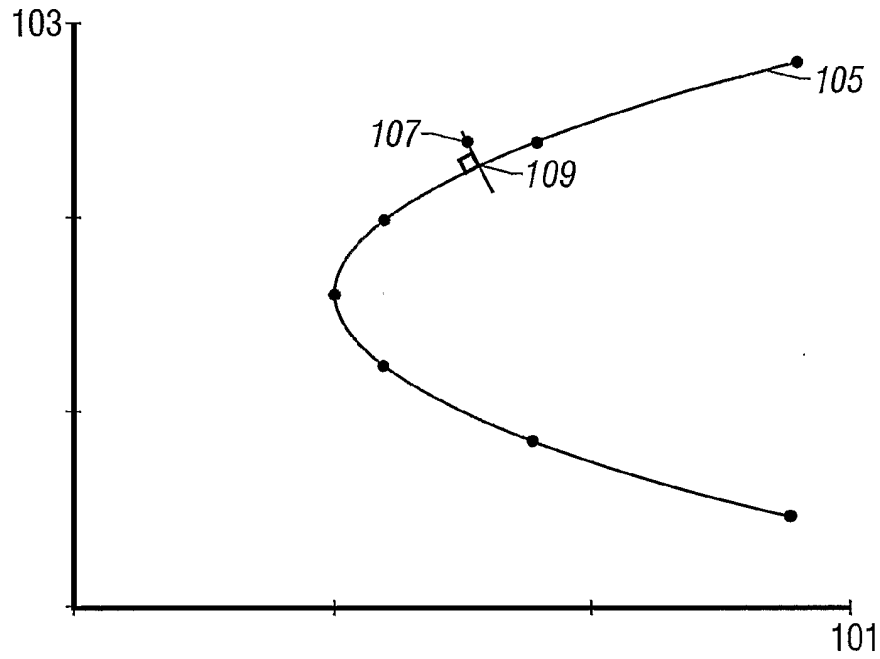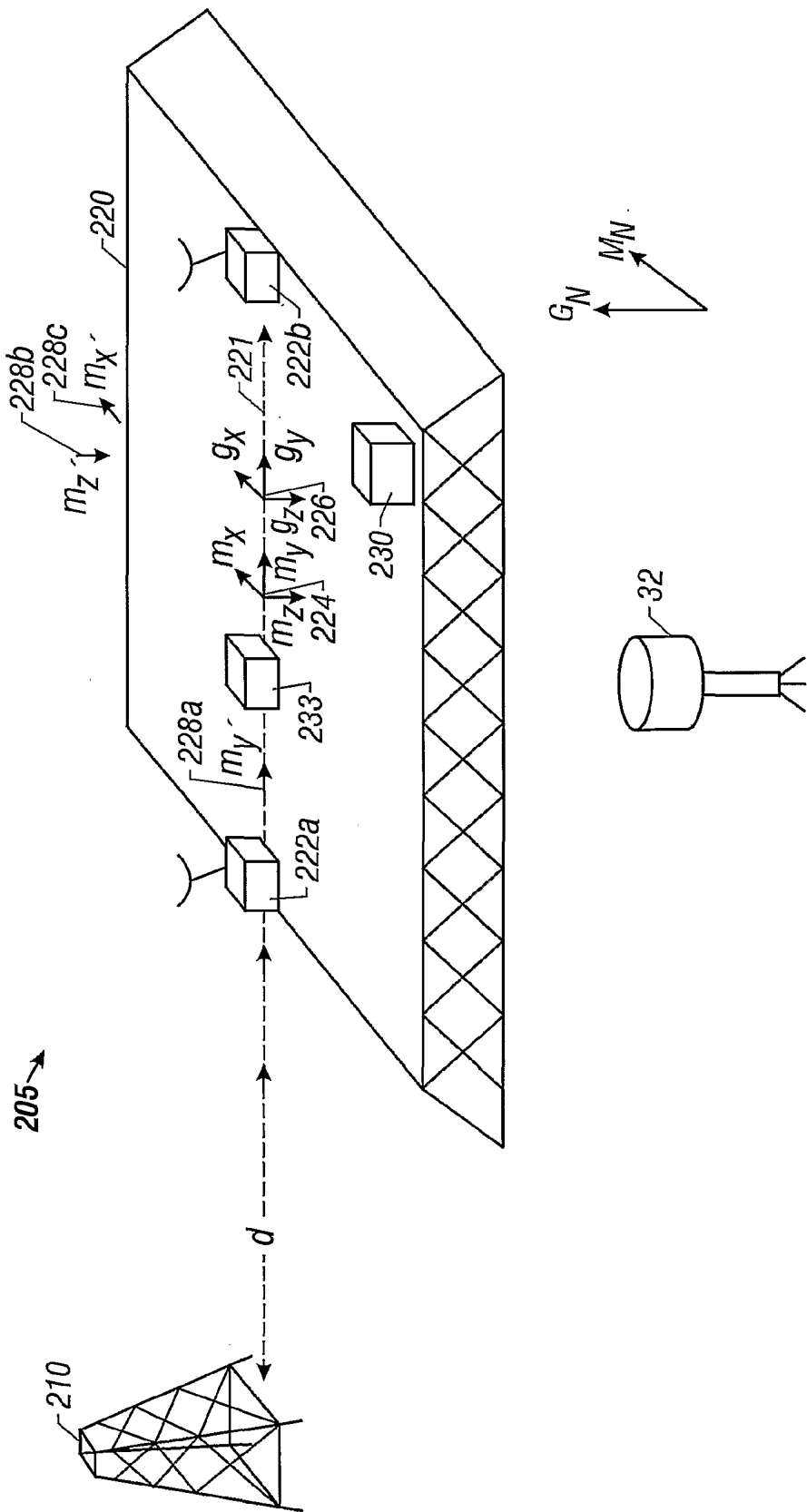
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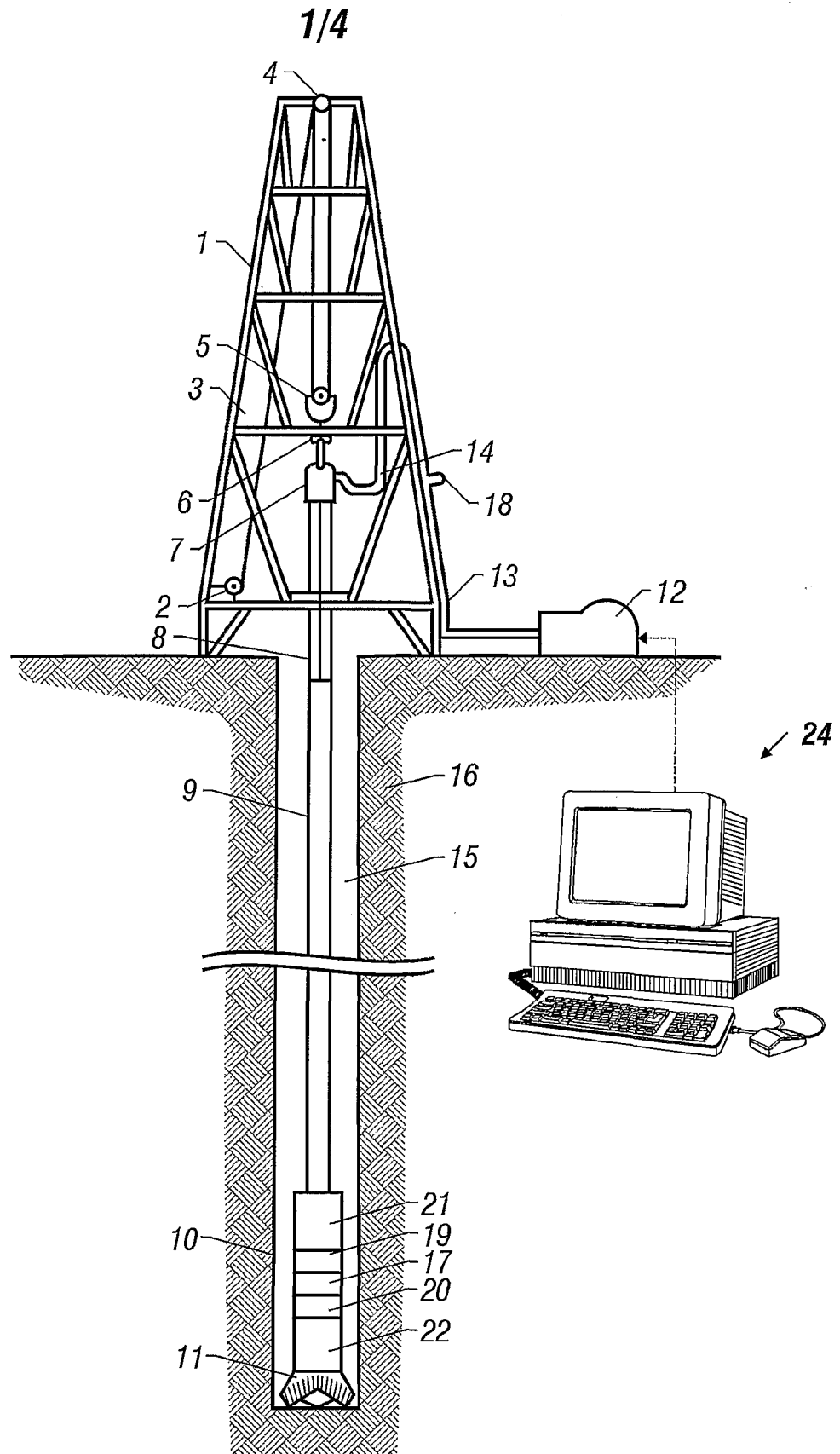
FIG. 2

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FIG. 3
(PRIOR ART)

FIG. 4

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FIG. 5